NASA Contractor Report 191437 Volume II

GASL TR 342

Mach 10 to 20 Electrothermal Wind Tunnel Feasibility Study and Demonstration

Final Report

Volume II
Experimental Study

by

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Prepared for
NASA Langley Research Center
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under

Contract NAS1-18450
Task Order 20

November 1991

ABSTRACT

The objective of this effort was to demonstrate operation of the key component of the Electrothermal Wind Tunnel (EWT), namely the liquid capillary arc. Operation of the liquid capillary arc requires pumping a cryogenic liquid into a continuous arc discharge, producing a stable effluence of high pressure, high temperature vaporized gas suitable for expansion through a supersonic nozzle. The immediate goals of this effort were production of up to 0.5 kg/sec of air at a capillary pressure of 10,000 psi (ultimately 60,000 psi) and a capillary temperature of 20,000°K for a period of 2 milliseconds. These conditions were chosen to match the capacity of the available capacitor bank at GT-Devices. Operation of the arc was successfully achieved, although with liquid nitrogen rather than liquid air, and at substantially reduced pressures, e.g. 4550 psi. A number of problems were encountered which are described in this report. However, none of the problems described above negate any of the anticipated capabilities of the liquid capillary arc or of the EWT concept. They do, however, indicate the need for further development effort on the cryogenic components of the system and on the arc. The effort on the cryogenic components is of a mechanical engineering nature associated with pumps and seals. The effort on the arc has to do with proper sizing for the starting process or proper temporal control of the fluid through the capillary. Additional effort is required to establish a steady effluence from the plenum section of the nozzle. The latter problem is probably more severe for the demonstration effort due to the short operating time than it would be for a full-scale facility.

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1. Introduction

1.1. Experimental objectives

The experimental program is a proof-of-principle demonstration that cryogenic liquids can be successfully injected into an operating high pressure, high temperature, capillary discharge without effecting the stability of that arc. Such a demonstration would prove the validity of the basic Electrothermal Wind Tunnel (EWT) concept.

Such a demonstration required completion of two primary tasks.

1) A suitable cryogenic pump needed to be developed which was capable of operating at pressures as high as 60,000 psi.

2) A capillary structure needed to be fabricated and tested with the pump injecting cryogenic liquids into an operating capillary discharge.

1.2. Description of experimental facility

All of the experiments to be described herein were performed on the U.S. Army AMCCOM GEDI railgun facility located at GT-Devices, Inc. The facility is shown in Figure 1. The use of this facility for the EWT program was with the kind permission of the U.S. Army. Utilization of this existing facility saved considerable funds and time in the performance of the present work. Essentially all system components required for testing the EWT were available from this facility, including: pulse forming network, high voltage charging power supply, high voltage switches, data acquisition system, computer, various diagnostics, large vacuum tank, vacuum pump, vacuum gauges, and safety systems.

1.3. Typical operating sequence

The ultimate program objective is to inject cryogenic liquids into an operating capillary discharge. It would be possible, in principle, to start the arc discharge first and then start pumping liquid into an already established arc. However, the relatively short discharges (2 msec) of the present experiment do not provide sufficient time for the pump to establish steady state flow. Thus, the pump must be activated first and establish a steady flow of liquid through the capillary before forming the arc discharge.

A typical sequence of events for a test run are as follows:

1) Assemble wind tunnel cartridge and pump.
2) Install external plumbing hardware for vacuum pumping and He gas flushing.
3) Install burst diaphragms if they are being used.
4) Evacuate electrothermal discharge module and vacuum tank to a few Torr.

5) Cool down cryogenic pump by filling dewar with LN_2 and maintaining full throughout the remainder of the test.
6) Fill cryogenic pump reservoir with cryogenic fluid.
7) Install manually operated actuating valve if used in place of burst diaphragms.
8) Activate cryogenic pump, establishing a jet of cryogenic fluid flowing through orifice, capillary, mixing chamber and exiting through nozzle throat into vacuum tank
9) As pump pressure rises through a preset value, the pressure transducer provides signal to trigger H.V. closing switch which initiates arc discharge after a preset time delay (typically 30 msec).
10) Initiating fuse quickly vaporizes, forming plasma arc discharge.
11) Cryogenic liquid continues to flow into capillary until $P_{capillary}$ exceeds P_{pump}.
12) Current decays to zero when charge on capacitor bank is depleted after 2 ms.
13) Cryogenic pump continues operating until reservoir is emptied.

Table I. Cryogenic pump parameters.

Main reservoir dimensions	Diameter - 1.984 cm Length - 17.3 cm Volume - ~55 cm^3
Piston stroke	~16.0 cm
Piston areas	Base - 2.85 cm^2 Head - 28.5 cm^2
Piston total length	33.53 cm
Pump overall length	~58 cm
Pump mass	~25 kg
Peak design pressure	60,000 psi (400 MPa)
Peak attained pressure	7902 psi at 293 deg K 4693 psi at 77 deg K

2.1.1. High pressure seals

The main high pressure seal is shown expanded in cross section in Figure 4.a. The seal and the seal ring are provided by Bal Seal, Inc., a well known source of cryogenic seals. The dimensions of the pump components were fabricated to the seal specifications provided by Bal Seal as their best suggested choice for a high pressure cryogenic sliding seal.

The seal consists of a carbon impregnated Teflon C-ring which is prestressed by an internal spring. This spring provides the initial contact loading required to make a seal before pressure onset. After the seal is exposed to high pressure, the pressure itself provides the required internal loading to make a seal. The piston shaft rides on a Teflon guide rider to prevent metal-to-metal contact.

The manufacturer would make no guarantee that these seals would work. They provided us with their best effort seal. We were, in fact, required to sign a waiver releasing the manufacturer from responsibility for the performance of these seals, since they were being operated far outside their usual specification range.

The piston is sealed on the low pressure side by the ring seal shown in Figure 4.b. The inside surface of the low pressure body is finished to 2-8 microinches to provide a smooth surface on which to seal and to reduce seal friction.

The main high pressure piston seal has caused the most difficulty of any item on this project. The high pressure cryogenic seal has never worked properly at LN_2 temperatures. Although a quasi-operational pump was finally attained, as detailed in Section 4 below, this was achieved only with great difficulty and at greatly reduced pressures.

Due to a shortage of funds, there was no time to stop and determine the exact cause of the seal failure at LN_2 temperatures.

2.1.2. External LN_2 dewar

Initial cryogenic tests with the pump utilized insulation wrapped around the outside of the pump and relied on cooling the reservoir to LN_2 temperatures by simply flowing LN_2 into the reservoir and out through a top vent hole. This approach turned out to be insufficient. However, by immersing the entire pump assembly in LN_2 the pump could be completely cooled down before attempting to fill the reservoir.

This was simply accomplished by enlarging the pump base flange diameter and welding a thin-walled stainless steel cylinder onto the flange. Figure 3 shows the arrangement. A layer of closed-cell foam is wrapped around the outside of the cylinder to provide thermal insulation. The usual cool down procedure is to first fill the external dewar with LN_2, and then fill the inside reservoir through the top feed hole. The reservoir will not fill with LN_2 unless a pressure relief vent is also provided.

LN_2 is supplied by 60 or 80 liter supply dewars operating at pressures of about 20-30 psia. A check valve in the feedline prevents high pressure from being communicated back to the supply dewar.

2.2. Pump actuating hardware

The transfer of helium gas from the storage plenum to the base of the piston must be accomplished on a time scale fast compared to the resulting motion of the piston. If it is not, the resulting slow pressure rise on the piston base will lead to ejection of LN_2 at pressures lower than desired. If it is too slow, all the LN_2 resevoir could even be emptied before the base pressure reaches the desired peak value.

In order to keep this time short, one must minimize the distance between the reservoir and piston base, and maximize the cross sectional area of the connecting transfer piping.

2.2.1. Double burst diaphragm

A double burst diaphragm system coupled to a pump is shown schematically in Figure 5.a. Operation is simple and straightforward. Plenum A is pressurized to the desired operating pressure, for example 1000 psi. Plenum B is pressurized to say half that value, 500 psi. The burst pressure for these diaphragms is nominally 750 psi. Pressure on the piston side of diaphragm B is atmospheric. Care must be exercised to bring up the pressures in the two plenums simultaneously so as to maintain pressure differentials across either disk that are less than its burst value.

The diaphragms are triggered to burst by venting the pressure in plenum B through a small orifice. In our experiments, venting to atmospheric pressure was adequate. When the pressure in B drops to 250 psi, diaphragm A will burst, followed in quick succession by diaphragm B. A small vent orifice is chosen so that significant pressure is not lost to the vent.

The venting valve is a solenoid actuated plunger type valve. The solenoid is battery powered and is switched actuated via a fiber optically coupled trigger signal. The valve is electrically isolated from the pump, which jumps to high voltage when the electrothermal module is fired.

Two versions of the double burst diaphragm system have been used in these experiments. The simpler version shown in Figure 5.a works only for operation at room temperature. When the dewar is filled with LN_2, the low temperature quickly reduces the pressure in plenum B after its gas pressurizing line has been removed. This causes a premature bursting of diaphragm A.

In order to operate at LN_2 temperatures, we employed a gas feed plenum to maintain the pressure in plenum B by continuously bleeding gas into the plenum through a second small orifice. This is shown in Figure 5.b. The pressures in plenums A and C are easily maintained at their initial pressures because they stay essentially at room temperature.

At LN_2 temperatures, the burst value for the diaphragms increases by about 28% to about 970 psi. This did not cause any difficulty, as we were always operating above this value.

2.2.2. Manually operated plug valve

During the free piston tests with LN_2, discussed below in Section 4, it was noticed that the pressure rise in the pump when operated by a manually operated plug valve was actually quite acceptable for these experiments. When pump "stuttering" problems arose that induced incorrect trigger signals from the pressure probe, we quickly switched from the burst diaphragm system to this approach.

Six shots, including the last two, were performed utilizing a manually operated Whitey Series P4T plug valve. It was actuated via a cord attached to its handle which was operated remotely from within the screen room. We found that a strong swift jerk of the cord could rotate the valve handle quickly enough to provide piston base pressure rises that exhibited smoother pressure rises than obtainable from the burst diaphragms.

Pressure probes are installed at the nozzle throat and in the ground electrode at the left of the mixing chamber.

2.3.3. Nozzle

The nozzle is fabricated out of brass. A replaceable throat is constructed of tungsten alloy. A simple conical structure was chosen to reduce cost at this stage of the experiment. The nozzle discharges into a 0.75 m^3 vacuum tank and has an area ratio of 256:1. The nozzle has not experienced any damage in these experiments.

2.3.4. Orifice

Several attempts were made to design and operate orifice tips which were heat shrunk into place on the end of the electrode stalk. Such a design would allow for somewhat cheaper parts. Unfortunately, these attempts were unsuccessful, and due to time constraints, we decided to fall back on the tried and true method of a screw-on orifice tip.

The orifice tip is shown in Figure 7. The orifice diameter is .060". The one circumferential and two short axial grooves are for attachment of the fuse to the tip. In these experiments an orifice tip experiences sufficient erosion after about two full capillary discharges that replacement is necessary. For those shots in which the current quenches early, erosion is significantly less and useful lifetime of the tips is extended.

2.4. High voltage circuit

The high voltage circuit is shown in Figure 8. It consists of four major subsystems; the pulse forming network, the high voltage switch, the power transmission line, and a protective spark gap.

2.4.1. Pulse forming network

The pulse forming network consists of 112, 250 μF, 10 kV capacitors configured to provide a nominal 2 msec pulse. This is achieved by arranging the capacitors in groups of four with approximately .8 μH inductors between each grouping. This arrangement provides a pulse forming network with a nominal .033 ohms impedance. A series ballast resistor provides additional resistance to match the power supply to the capillary discharge load, which has a nominal resistance of .100 ohms.

2.4.2. High voltage switch

Switching is accomplished with a pair of General Electric Model GL-37207A ignitrons rated at 25 kV and 300 kA. The ignitrons are triggered via FS-10 units which deliver a 300 ampere, 3 kV pulse to the ignitor circuit of the ignitron upon receipt of a fiber optic trigger signal. The FS-10 units are each powered by a 36 V battery in order to maintain electrical isolation from the rest of the high voltage system. The units are manufactured by Reynolds Industries, Inc. for use as exploding bridgewire detonators.

2.4.3. Transmission line

Transmission lines consisting of parallel copper busbar .25" x 1.00" run from the ignitrons to the connect point at the EWT, a distance of about 10 meters. The lines are separated about 1" by insulating blocks spaced every 12 inches. Multiple turns of fiber tape are used to prevent the conductors from separating under the magnetic forces.

2.4.4. Spark gap

Considerable damage occurred on Shot 7 due to a high voltage spike which caused an arc to form between the positive high voltage electrode and the case of the capilllary chamber. A spark gap set to break down at 8.4 kV was subsequently installed across the capillary discharge to prevent any future voltage spikes from damaging the hardware. The spark gap is indicated in Figure 8.

2.5. Diagnostics

2.5.1. Voltage

High voltage across the capillary is measured with a Pearson Model 411 current transformer and a shunt resistor. The shunt resistor consists of a string of carbon resistors with a total resistance of 25 kΩ. 50 turns of wire are looped through the center of the current transformer to provide the desired resolution. The circuit is shown in Figure 9. The probe has a calibration of 10 kV/volt when the output is terminated in 50 Ω at the scope.

2.5.2. Current

A passively RC integrated Rogowski coil is used to measure current. The coil is calibrated against a Pearson Model 1423 current transformer whose output signal is directly proportional to the current looping its center.

2.5.3. Pressure

Pressures in both the cryogenic pump and in the electrothermal discharge module are directly measured with piezoelectric pressure transducers. A PCB Model 119A is used in the pump, while virtually identical Kistler Model 217C transducers are used in the electrothermal module.

The mounting configuration for all probes is the same and is shown in Figure 10. All three probes are electrically connected to its local ground, and powered by its own independent battery operated power supply. Connection to the digitizer in the screen room is via fiber optic link. Fiber optic links are absolutely necessary in pulsed high voltage systems because probes would otherwise be damaged by unavoidable ground loop currents.

These pressure transducers generate an output voltage directly proportional to the pressure. They can measure peak pressures of 80,000 psi with a time response of 1 microsecond, more than adequate for the EWT experiments. The PCB 119A is rated by the manufacturer for operation to -400 °F. Calibration of the transducer changes by only .01% per °F. This yields an approximately 4% calibration error at LN_2 temperatures.

The pump pressure transducer does more than just provide a measurement of the pump pressure. Initiation of the capillary discharge is triggered by a preset point on the rising slope of the pressure signal.

3. Summary of Experimental Tests

A brief summary of the tests performed is given in Table II. The tests listed with a shot number indicate those tests in which data was written to floppy disk for permanent storage. All other tests did not require permanent storage, and any data from these tests was stored as hard copy printouts of the scope traces and/or written notes in a lab book.

This summary is presented here for documentation and for reference in the following sections and as an accounting of the development sequence. Selected shots are discussed further in Sections 2 and 3 below.

Even though pump development and capillary discharge experiments were pursued simultaneously, they are essentially two separate issues which can be treated independently. In Sections 2 and 4 we will discuss each of these two topics pretty much independently of the other, making links where appropriate. Reference to Table II can always show how each effected the other.

For nomenclature regarding pump regions and plenums please refer to Figures 3 and 5.

Table III. Pressure differential vs. mass flow rate for .060" orifice.

Pressure differential (psi)	Mass flow rate (kg/sec)
1000	.113
5000	.254
10,000	.359
60,000	.878

The design of the orifice itself is constrained not only by the dimensions of the capillary, but also by the fact that the orifice tip typically needs to be replaced after each shot due to arc damage. A removable orifice is screwed onto the tip of the electrode shaft as shown earlier in Figure 7.

An interesting effect is observed on all these tests. A transient oscillation in the pump pressure is observed to occur immediately after diaphragm bursting (see Figure 12), with a frequency of roughly 250 Hz. The oscillation lasts for about 20-25 ms. This is believed to result from the compressibility of the fluid.

The piston and the water can be modeled as a mass/spring system using the compressibility of the water to provide an effective spring constant. The effective spring constant would be given by

$$\kappa = \frac{BA}{L},$$

where B is the bulk compressibility of the fluid, A is the cross sectional area and L is the length of the fluid reservoir. The frequency of oscillation is then given by

$$f_{osc} = \frac{1}{2\pi}\sqrt{\frac{\kappa}{m}} = \frac{1}{2\pi}\sqrt{\frac{BA}{mL}},$$

For piston mass m=2.33 kg, reservoir length L=7 in, area A=.78 in^2, and taking 3.16×10^5 psi for the bulk compressibility of water, this frequency is about 204 Hz. This is very close to the observed frequency. The wave dissipates rapidly and causes no real experimental difficulty. The mass flow rate of cryogenic fluid into the capillary will be constant, as long as triggering of the arc discharge is delayed until after the transient oscillation has decayed away. In these experiments this delay was typically set at 30 milliseconds.

4.2. Results of pump tests with LN_2

4.2.1. Problems encountered on initial tests

Initial attempts to cool the pump down to a temperature where the main reservoir could be filled with LN_2 showed very quickly that our insulation techniques were insufficient and the entire pump needed to be immersed in LN_2.

This was accomplished by increasing the diameter of the original pump base flange and welding a stainless steel cylinder to this new flange. The resulting dewar was insulated on the outside with closed cell foam insulation. Figure 3 shows the resulting geometry. Although this is not an ideal solution, it was expedient, and sufficient.

After a series of tests, outlined in Section 3, in which no pressure data was obtained on firing the pump, it became clear that the piston was actually not moving, or at least moving so slowly as to be of no consequence. On one of these tests a loud screeching or grinding noise was heard several seconds after the diaphragms burst. Discussions as to why this should occur centered around the possibility of water vapor condensing and freezing on the inside surfaces of the pump during the cool down cycle. Such a phenomenon could impede piston motion due to the high strength of water ice at LN_2 temperatures.

One other minor problem occurred when a double burst diaphragm system was first used at LN_2 temperatures. The downstream diaphragm is in essentially direct contact with metal that is part of the LN_2 dewar and hence is at 77 degrees K. Because of the small heat capacity of the gas in the region between the two diaphragms, the temperature of the gas will quickly equilibrate with that of the downstream diaphragm. Since the gas density cannot change, the pressure drops correspondingly. If drops to a low enough value that the pressure differential across the upstream diaphragm is above the diaphragm rating, it will burst.

Premature bursting of the diaphragms can be prevented by allowing the density of the gas between the diaphragms to increase as required to maintain constant pressure as the temperature is dropping. This is easily accomplished by allowing the gas to communicate with a second pressurized plenum through a small orifice. This was discussed in more detail in Section 2.2.1

4.2.2. Free piston test series

A series of tests were initiated to test the freezing piston hypothesis. The pump was reconfigured with the addition of external plumbing and valving to allow manual control of the atmosphere inside the pump during the cool down cycle. The setup is shown schematically in Figure 13.a. These tests were called free-piston because they were performed in such a way that the piston could be moved up and down by the manual control of gas pressure on either side of the piston.

4.2.2.1. Procedures

The operating procedures are simple in principle. Evacuate the pump reservoir, called Region C in the Figure, and also Regions A and B down to a few Torr and backfill with helium gas, flushing several times. While leaving the three Regions pressurized to slightly over atmospheric pressure with helium gas, cool down the pump by filling the external dewar with LN_2. As the pump cools down, bleed in sufficient helium gas to maintain this pressure slightly above atmospheric. This prevents any water vapor from entering the system through any vacuum leaks. We learned later that controlling the atmosphere of Region A was not necessary.

Once the pump has cooled down, the top pressure gauge is removed and an insulated LN_2 feed line is connected to the top port. At the same time, the fitting on the output port of Region C is removed to allow pressure to vent. Now begin filling the reservoir with LN_2 from the supply dewar. The pressurized stream of LN_2 vapor exiting the vent port prevents water vapor from entering through the vent port.

Once Region C is filled with LN_2, as evidenced by a steady stream of LN_2 from the vent port, the fittings for the burst diaphragms or manually operated valve can be attached to the base of the pump. We later learned that it was not necessary to control the atmosphere in Region A, thus making it possible to assemble the burst diaphragm system from the very beginning. Any water ice forming on the inside surfaces of Region A apparently does not impede piston motion. When a manually operated plug valve was used, it was not connected until the last possible moment because of its tendency to freeze up quickly. In this case, we usually placed a temporary piece of tape across the bottom port for good measure.

The schematic diagram in Figure 13.b. shows the changes to the configuration used for actual wind tunnel tests.

4.2.2.2. Test observations

Using the procedures described in the last section, we were able to obtain free piston motion by appropriate manual operation of the valves. However, pump operation was still far from ideal. The high pressure seal between Region B and the main reservoir, Region C, appeared to leak LN_2 from the reservoir into Region B. Several attempts to eliminate this seal leakage by replacing seals with tighter seals and by using carefully fabricated insertion tools suggested by the manufacturer, were unsuccessful. Extensive discussions with the manufacturer also shed no light on the problem.

Although the seal leakage problem was indeed a serious problem from a long term point of view, it was decided to continue testing with some further modifications to the pump which would minimize the effect of a bad seal. These issues are discussed below in more detail.

Results of Shot 11

In Shot 11, we made our first successful attempt to measure pressure in the pump reservoir during cryogenic pump operation. The plenum pressure was only 500 psi. The pressure trace in the main reservoir is shown in Figure 14. The pressure reached a maximum of 693 psi, not very high, but not unexpected since a manually operated plug valve is used instead of burst diaphragms, and more importantly, the fluid which leaked into Region B must exit through relatively small vent holes.

Shot 11 was observed to operate successfully in liquid mode. A high speed jet of LN_2 was observed to be ejected from the orifice which knocked over a large cardboard box set up as a target. The apparent pulse time of the jet agrees with the approximately .25 sec seen on the pressure trace.

Results of Shot 12

Since the seals appeared to be unfixable in the time available, we needed a way to continue tests while somehow working around the limitation. In order to increase the effective output pressure, larger vent holes were provided for the fluid in Region B to exit through. This was accomplished by removing one of the fittings on the two access ports in Region B and replacing it with a piece of Teflon tape. The tape is held in place by its adhesive and by several turns of wire around the body of the pump to help keep it from curling during exposure to LN_2. This technique worked very well. Figure 15 shows the configuration.

The tape allows Region B to still be pumped down to vacuum through the other fitting, while providing a large vent hole for fluid to exit once the piston starts moving. On Shot 12 the Teflon tape was manually punctured just prior to pump activation to minimize any possible initial impedance to liquid flow. We later learned that this was not necessary.

While still using the same 500 psi in the gas plenum as on Shot 11, we obtained nearly four times the peak pump pressure, as shown in Figure 16. The peak pressure was 2229 psi. The pulse time also decreased to about 160 milliseconds. Such a pulse time corresponds to a mass flow rate of .275 kg/sec, and an average piston velocity of 1.0 m/s. The piston velocity is controlled primarily by the mass flow rate through the orifice and not by the mass flow rate out of Region B.

Even though the high pressure seal leaks both ways, the fluid in Region B is mostly ejected through the two side access ports which are lower impedance paths than back through the presumably small leak area around the seal.

Due to pressing time and funding constraints, our objectives had changed to one of simply getting a pump operating well enough that arc discharge experiments could continue. Perfection of the pump was no longer a goal. So we accepted this somewhat less than ideal performance and shifted to capillary discharge experiments using this pump configuration.

4.2.3. Reconfigured pump tests

Shots 11 and 12 showed that the problem of a freezing piston had been solved by eliminating all water vapor from the inside of the pump prior to cooling down to LN_2 temperatures. Reliable operation of the pump had been obtained but at somewhat lower pressures than desired. Most of the pressure loss was due to various seal leakage problems, but some was simply due to operation with a manually operated plug valve. Peak pressures could be increased by switching back to burst diaphragms. Before moving ahead with a full up wind tunnel test, one more test needed to be performed in which burst diaphragms were tested and in which the procedures would be identical to those which would be used on a real wind tunnel test.

Results of Shot 13

The double burst diaphragm system was installed at the very beginning prior to the initial cool down procedures. This was a bench test again so that visual observation of the liquid jet from the orifice could confirm pump operation unambiguously.

The burst plenum pressures were set at 875 and 500 psi. When the pump was actuated, a short pulse-width, high pressure jet of liquid was ejected from the orifice. Figure 17 shows the pressure trace obtained from the pressure transducer in the main reservoir. The peak pressure jumped to 4316 psi after a short low amplitude pressure ledge. The pulse width was reduced to 80 ms.

Although this performance was not close to ideal, it was sufficiently good that capillary discharge experiments could be restarted.

5. Capillary Discharge Experiments

5.1. Baseline arc discharges without liquid injection

One test, Shot 4, was performed to establish the baseline performance of the capillary without liquid injection into the capillary. Such a test is very similar to the hundreds of tests that have been performed at GT-Devices on Electrothermal gun systems.

Figure 18 shows the current and voltage from Shot 4. This test was performed with an initiating fuse consisting of a bundle of 16 125 μm aluminum wires. The capillary length was 13 cm. Peak power input was ~39 MW. Figures 19 and 20 show the measured pressures at the ground electrode and at the nozzle throat. These test results are pretty much as expected, and establish that the capillary system performs properly in the absence of liquid injection.

5.2. Arc tests with water injection

5.2.1. Arc quenching

The primary result obtained from the initial tests with water injection was the occurrence of arc quenching. Figure 21 shows the current and voltage for Shot 3. The current peaks at about 11 kA at 44 usec and decays almost to zero by 468 usec. An external H.V. breakdown occurred at this time due to faulty insulation, and the large voltage spike which occurs when the arc tries to extinguish.

Several attempts to prevent this arc quenching by using more massive fuses were not successful due to problems with orifice ejection which damaged the fuses. Although we were confident of solving this problem, we did not want to spend the time and effort on water injection studies. So we abandoned further water experiments and went on to LN_2 experiments, with the expectation of solving the quenching problem with LN_2.

5.2.2. Arc initiating fuse

One particular problem of some importance that arose during the water injection experiments was the occurrence of large voltage spikes when the fuse wires vaporize. Voltage spikes occur when the fuse transitions to a vapor. In the vapor state the fuse resistance becomes very large during the brief time before sufficient ionization has occurred to increase conductivity. Circuit inductance tries to maintain a constant current through a suddenly much larger resistance, inducing a momentary spike in the voltage across the capillary.

We solved this problem by constructing fuses as shown in Figure 22. The tapered fuse prevents large voltage spikes by limiting the length of the arc, during the initial vapor burst phase, to a very short length. As the initial vapor heats and ionizes it also grows in length, but at a rate that can be controlled by the taper of the fuse. Circuit current can now readjust in such a way that large voltage spikes are significantly reduced.

The fuse is rolled up into a tight roll lengthwise as indicated in the Figure. One end of the fuse is sandwiched between the ground electrode and the capillary end face, while the other end is wrapped around the orifice tip in the grooves shown earlier in Figure 7. The fuse is flattened against the inside wall of the capillary so that it is not in the direct path of the fluid jet emerging from the orifice. No problems were ever observed with the fluid jet damaging the fuse.

5.3. Arc tests with LN_2 injection

5.3.1. Low pressure injection from supply dewar

One test, Shot 8, was performed in which the pump was bypassed and LN_2 was fed directly from the supply dewar into the capillary. Problems with the cryogenic pump were directly bypassed to allow demonstration of a wind tunnel test with nitrogen vapor in the capillary at the time of arc initiation.

LN_2 was allowed to flow through the orifice for two hours before initiating the discharge. Data from the shot is shown in Figures 23 to 25. The results are similar to those obtained in Shot 4 in which there was no liquid or vapor injection. Data from Shot 4 was shown previously in Figures 18 to 20. This is to be expected since the quantity of nitrogen in the capillary was certainly very small and the mass flow rate was extremely low, about .015 kg/sec. It is unknown whether nitrogen liquid or vapor was flowing through the capillary at the time of discharge initiation, although the latter is more probable.

5.3.2. High pressure pump injection

After the cryogenic pump development tests were completed with Shot 13, tests were resumed with full wind tunnel shots. We immediately ran into the same problem that occurred with the water injection tests, namely, arc quenching.

<u>Results of Shots 14-17</u>

Figure 26 shows voltage and current data from Shot 14. Current flows for a brief 200 μsec before extinguishing. The pump pressure, shown in Figure 27 rose to a peak of 4693 psi for plenum pressures of 1000 and 500 psi. Incidentally, this pressure trace is the best obtained from the cryogenic pump to date.

Attempts were made to eliminate quenching, first on Shot 15 by installing a beefier fuse which would allow current to grow to larger value before fusing, and then on Shot 16 by increasing the charge voltage on the capacitor bank in addition to the beefier fuse.

Current was increased and the lifetime was somewhat increased by these efforts, but the current still quenched.

An attempt on Shot 17 to reduce the liquid flow rate into the capillary by reducing the size of the orifice to .030" from the usual .060" was unsuccessful for a different reason. The reduced flow rate was so slow that the pump reservoir never filled with LN_2 during the ~2 hours that it was allowed to flow. Hence, a trigger signal was never generated by the pressure transducer, which prevented the high voltage switch from closing and initiating a capillary discharge. The voltage on the capacitor bank was subsequently discharged by the safety system.

Results of Shot 18

With Shot 18, we returned to our standard orifice size of .060". Instead of triggering the bank after the usual 30 ms delay after receipt of trigger from the pressure transducer, which had been set to trigger at ~500 psi on the rising edge of the pressure, we decided to trigger the bank prompt at the 1000 psi pressure level in the pump. Again, this was an attempt to reduce the liquid flow rate into the capillary by triggering at a significantly earlier time in the pump operation when the pressure was lower.

The current is shown in Figure 28, and the pressure in Figure 29. At first glance this appears to be a very successful test. The current starts to quench, but recovers and then lasts for the entire 2 ms pulse time of the power supply. Unfortunately, a closer look at the pressure trace reveals that the current was actually triggered on the first of what appear to be a series of "stuttering" pressure pulses at the very beginning of piston motion as seen in the expanded pressure trace in Figure 30.

Results of Shot 19

Thinking that the main high pressure seal was again causing problems, we removed the seal entirely for Shot 19, deciding to trade high pressure operation for a reproducible pressure trace from which a reliable trigger signal could be obtained.

Unfortunately, this did not work either. Similar pressure pulses were observed.

Results of Shots 20-21

Since we did not have time to perform any more pump development tests, old test data was reviewed looking for a quick way to achieve a smooth, noise-free, rising pressure trace which could provide a reliable trigger signal. It was noticed that the rising pressure trace obtained with plug valve actuation of the pump, as seen in Figure 16, was very smooth.

A quick bench test, Shot 20, to determine whether this was reproducible, showed that it was. The pressure trace is shown in Figure 31. The pressure was lower than with burst diaphragms of course, but at least a clean trigger signal could be obtained.

Based on this encouraging result, a full wind tunnel test was performed on Shot 21 using a plug valve pump actuator. The discharge was successfully triggered at the desired 1000 psi point, however, the discharge still quenched. Figure 32 shows the resulting current and voltage.

5.3.3. Analysis of arc quenching

Up to this point, our working hypothesis for why arc quenching was occurring was that the rate of liquid flow into the capillary was too high and was essentially blowing out the arc. Several tests, culminating with Shot 21 suggested that this was probably not the case.

Further analysis after Shot 21 pointed to the possibility that the cause was due to the initial mass of liquid in the capillary at the time of arc initiation. This mass is contained in the small diameter liquid jet flowing along the capillary axis, which is established by the cryogenic pump during the 30 ms before arc initiation.

The amount of liquid in the capillary at the time of arc initiation is given by

$$m = \rho \frac{\pi d^2}{4} L,$$

where, ρ=0.8 gm/cm^3 is the density of LN_2, L is the capillary length, and d is the orifice diameter. For L=13 cm and d=.060"=.152 cm, this mass is .188 gm. A total energy of 5.64 kJ is required to heat this initial mass of nitrogen to 10,000 °K, at an enthalpy of 3x10^7 J/kg
at that temperature. The energy dissipated in the arc in Shot 21, up to peak current at 70 μsec, is only 963 Joules, a factor of nearly six lower than that required to heat the entire liquid jet to 10,000 °K.

Close inspection of the voltage and current waveforms in Figure 32 suggests the following scenario of events. The tapered fuse first vaporizes at its narrowest end near the capillary exit electrode. This occurs at roughly 38 μsec, which agrees well with the calculated initial burst time. The resulting arc grows in length as the tapered fuse burns back. Since the arc has a higher resistivity than the original aluminum foil, and because the current is still increasing, the voltage rises very rapidly during the next 35 μsec. During this time the total resistance is also increasing rapidly from a low of about .020 Ω at initial burst to about .130 Ω at 70 μsec. The power input during this time is not heating the plasma as evidenced by the increasing resistance as the current rises. The bulk of the power is instead going into vaporizing more and more liquid from the jet at the center of the capillary.

After about 70 μsec, the capillary resistance is dominated by plasma resistivity, since the fuse is essentially burned back completely. This time agrees roughly with the calculated burn back time based on the action integral of the current. After about 70 μsec, the PFN can no longer maintain the current level against the rapidly rising resistance and the current begins decaying. As the current decays, the temperature also decays, which in turn causes the resistance to continue to rise. This feedback loop continues until the current completely quenches around 210 μsec.

When the capillary was initially designed it was not appreciated how rapidly the liquid jet would vaporize and effect the conductivity of the capillary, an important lesson for the future design of cryogenically pumped wind tunnel capillaries.

5.3.4. Results of two successful tests

The last two test shots of this program were performed to test a possible quick solution to arc quenching, by reducing the amount of liquid in the capillary at arc initiation. The most obvious approach would have been to reduce the diameter of the orifice. However, experience from Shot 17 showed that this approach led to difficulties in filling the cryogenic pump LN_2 reservoir. An alternative approach, also easily implemented, was to reduced the capillary length. Of course, this has two effects. It not only reduces the liquid mass, it also increases the electric field strength if the voltage is maintained constant. Both of these effects act to improve the ability of the circuit voltage to drive current through the capillary discharge.

Reducing the capillary length was successful. On Shot 22, a plenum pressure of 600 psi was used, yielding a peak pump pressure of 2571 psi. The pressure trace is shown in Figure 33. The current and voltage traces are shown in Figure 34. Triggering of the discharge occurred at the correct time (1000 psi on the rising edge), and quenching did not occur.

A second test, Shot 23, was performed at a plenum pressure of 1200 psi, twice that of Shot 22, and the bank voltage was reduced slightly to reduce capillary pressure. The purpose was to try to operate the pump at a higher pressure than the capillary. Figure 35 shows the pump pressure. Figure 36 shows the current and voltage.

The capillary exit pressure measured at the electrode rises to a relatively constant value of about 3700 psi throughout most of the current pulse, as shown in Figure 37. The pressure in the nozzle throat rises to a peak of about 2200 psi, shown in Figure 38. The stagnation pressure at the orifice is about a factor of two larger than that measured at the electrode. This means the liquid flow from the pump was cut off early in the discharge. This has a visible effect on the pump pressure as seen by the transient pressure peak during the time of the discharge. The pump recovers, though, and continues pumping.

As noted in the last Section, the success of this technique can be attributed partly to the reduced initial liquid mass and partly to the increased electric field strength. Future calculations and experiments will be required to determine the most appropriate capillary length for a given operating voltage. Note, however, that this is not really an issue for longer pulse length devices. In such devices the arc can be established either simultaneously with or just prior to injection of LN_2 and the capillary will not have a liquid jet fill to contend with.

6. Summary

6.1. Cryogenic pump

At the beginning of this effort, it was recognized that the most difficult task would be the development of a cryogenic pump capable of operating at a pressure of 60,000 psi. This has indeed turned out to be the case. Unfortunately, much of the experimental effort in this program was expended trying to get the cryogenic pump to operate well enough to perform wind tunnel tests. This effort was only partially successful. Because of this, only a few data shots were obtained with cryogenic liquid injection into an arc discharge. Thus, discharge characterization is rather limited, although the data that was obtained is encouraging.

Pump performance deficiencies were traced to two primary problems. Freezing of the piston, and high pressure seal leakage at cryogenic temperature.

Piston freezing was eliminated by developing procedures to control the interior atmosphere of the pump both during the initial cool-down cycle and throughout the entire test. These procedures, which incorporated some external plumbing hardware, eliminated water vapor from the system and prevented its entry during the rest of the test. Thus the problem of freezing piston appears to be solvable by proper design and procedures.

The problem of seal leakage at cryogenic temperature is a different story. Even though the high pressure reciprocating seal was not specifically rated for operation at 60,000 psi, it should at least have sealed under the static conditions present during the initial cool-down cycle. This was not the case. The seal leaked even under static conditions with very low pressure differential across the seal, essentially that of the supply dewar, which was only about 20-30 psia.

Attempts to definitively identify why this leakage occurred and to eliminate it were unsuccessful in the time available. In spite of the seal leakage, however, we were able to establish procedures whereby the pump could still be successfully operated, although at reduced performance levels. This involved providing large vent holes in the central cavity through which leaked fluid could be expelled during pump operation. Although this was only partially successful, it was sufficient to allow pump operation at pressures up to ~4600 psi for ~1000 psi gas pressure on the piston base. Extensive further efforts to eliminate seal leakage were abandoned in favor of continuing capillary discharge experiments at the attainable reduced pump performance level.

The present cryogenic pump has obviously caused a great deal of difficulty. However, the basic intensifier design philosophy appears to be valid. The two main problems have been implementation of the cryogenic seal, and proper cooling of the entire pump assembly. The former can probably be fixed by a more careful thermal and seal design. The latter can readily be fixed simply by immersing the entire pump assembly in a LN_2 bath, as opposed to the "quick and dirty" after the fact dewar design used in these experiments. Although we cannot be at all satisfied with the cryogenic pump performance to date, it is a relatively small piece of hardware and we believe that neither of these fixes should be very expensive to implement. An investigation into alternative cryogenic pump approaches is perhaps warranted.

6.2. Capillary discharge

The phenomenon of arc quenching was observed early in the program when attempts were made to inject water into a capillary discharge. Rather than spending time trying to eliminate arc quenching with water, with the possibility of having to resolve it again with cryogenic fluids, we waited until experiments with cryogenic fluids was possible. Arc quenching quickly reappeared with cryogenic fluid injection.

Initial hypotheses to explain arc quenching focused on the rate at which liquid was being injected into the capillary. It became clear, however, that this had nothing to do with the problem. Arc quenching was caused very simply by trying to initiate an arc in a capillary that contained too much initial fluid mass, whether water or cryogenic fluid did not matter particularly. This mass prevented the arc from attaining the necessary temperature and, hence conductivity, required to maintain the arc at the given voltage level. A positive feedback loop between suppressed conductivity and suppressed current was established which caused the arc to extinguish.

By shortening the capillary, while maintaining essentially the same voltage, the liquid mass is reduced and the available voltage can establish and maintain a stable arc. Two experimental tests were performed in which the capillary length was reduced from 13 cm to 5 cm. A stable arc was successfully established and maintained in both tests, partly due to the decreased liquid mass and partly due to the increased electric field strength.

This quenching problem only occurs in these experiments due to the short discharge time available from the power supply which forces a delay between pump initiation and discharge initiation if steady state pump operation is desired. This introduces a significant total liquid mass in the capillary at the time of discharge initiation. This problem is avoided altogether by either starting the liquid flow after the arc has been established, or at the same time. Both options would be possible in a long pulse experiment of 10's to 100's of milliseconds.

Because of cryogenic pump problems, the pump pressure was less than the peak plasma stagnation pressure in the capillary on these last two tests. Hence the mass flow rate necessarily dropped to zero relatively early in the discharge. However, the lack of any deleterious effects on the arc discharge during the current rise time when $P_{pump} > P_{capillary}$ is strong evidence that the arc would have survived a higher injection pressure.

None of the problems described above negate any of the anticipated capabilities of the liquid capillary arc or of the EWT concept. They do, however, indicate the need for further development effort on the cryogenic components of the system and on the arc. The effort on the cryogenic components is of a mechanical engineering nature associated with pumps and seals. The effort on the arc has to do with proper sizing for the starting process or proper temporal control of the fluid through the capillary. Additional effort is required to establish a steady effluence from the plenum section of the nozzle. The latter problem is probably more severe for the demonstration effort due to the short operating time than it would be for a full-scale facility.

It should be emphasized that the difficulties encountered in this program have been associated primarily with the development of a cryogenic pump, and not with the operation of the capillary cartridge. Establishment of a stable arc discharge appears to be relatively straightforward, as suggested by the last two test shots in this program.

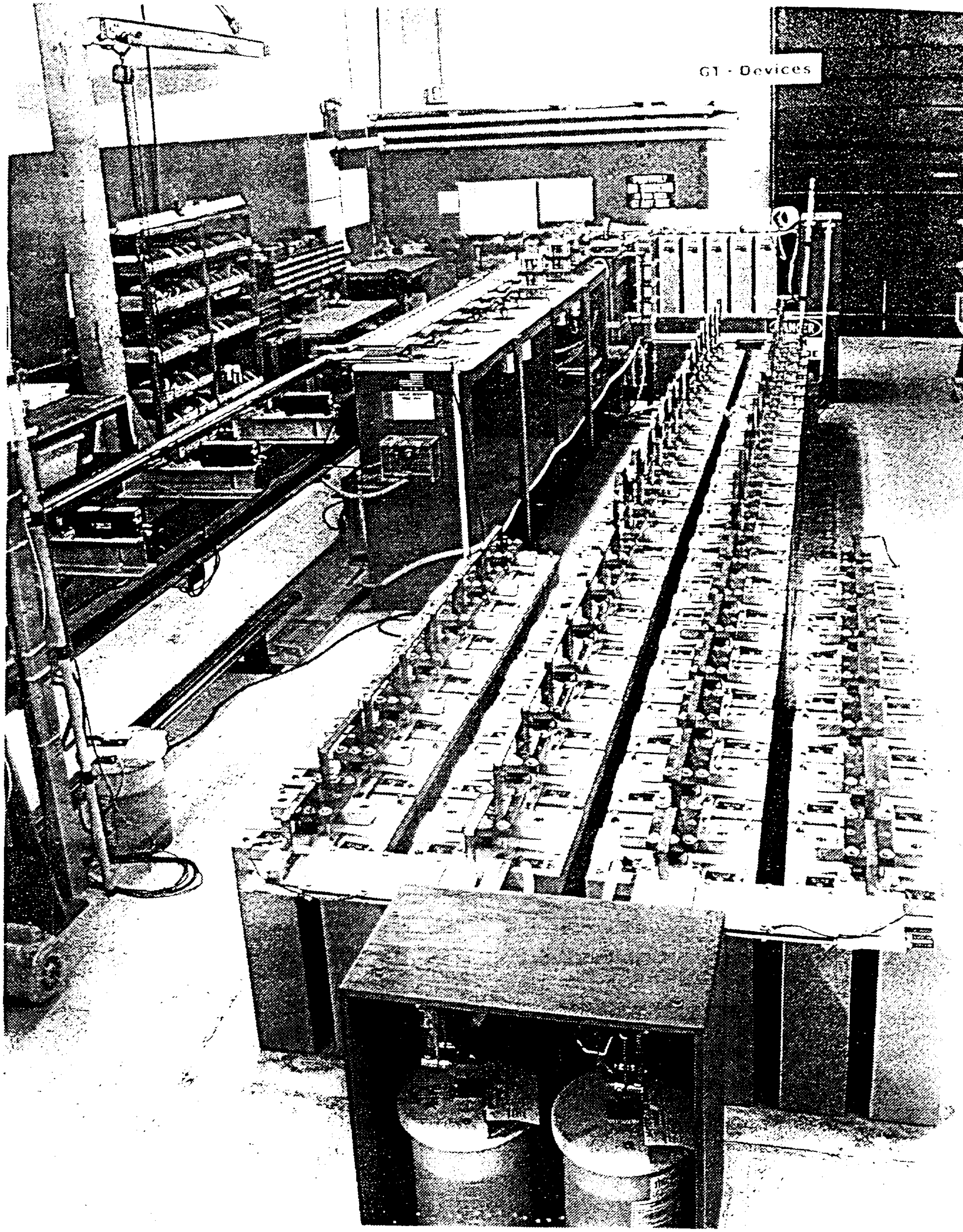


Figure 1. GEDI railgun facility at GT-Devices showing 1.4 MJ pulse forming network in foreground which acts as the power supply for the Electrothermal Wind Tunnel experiments.

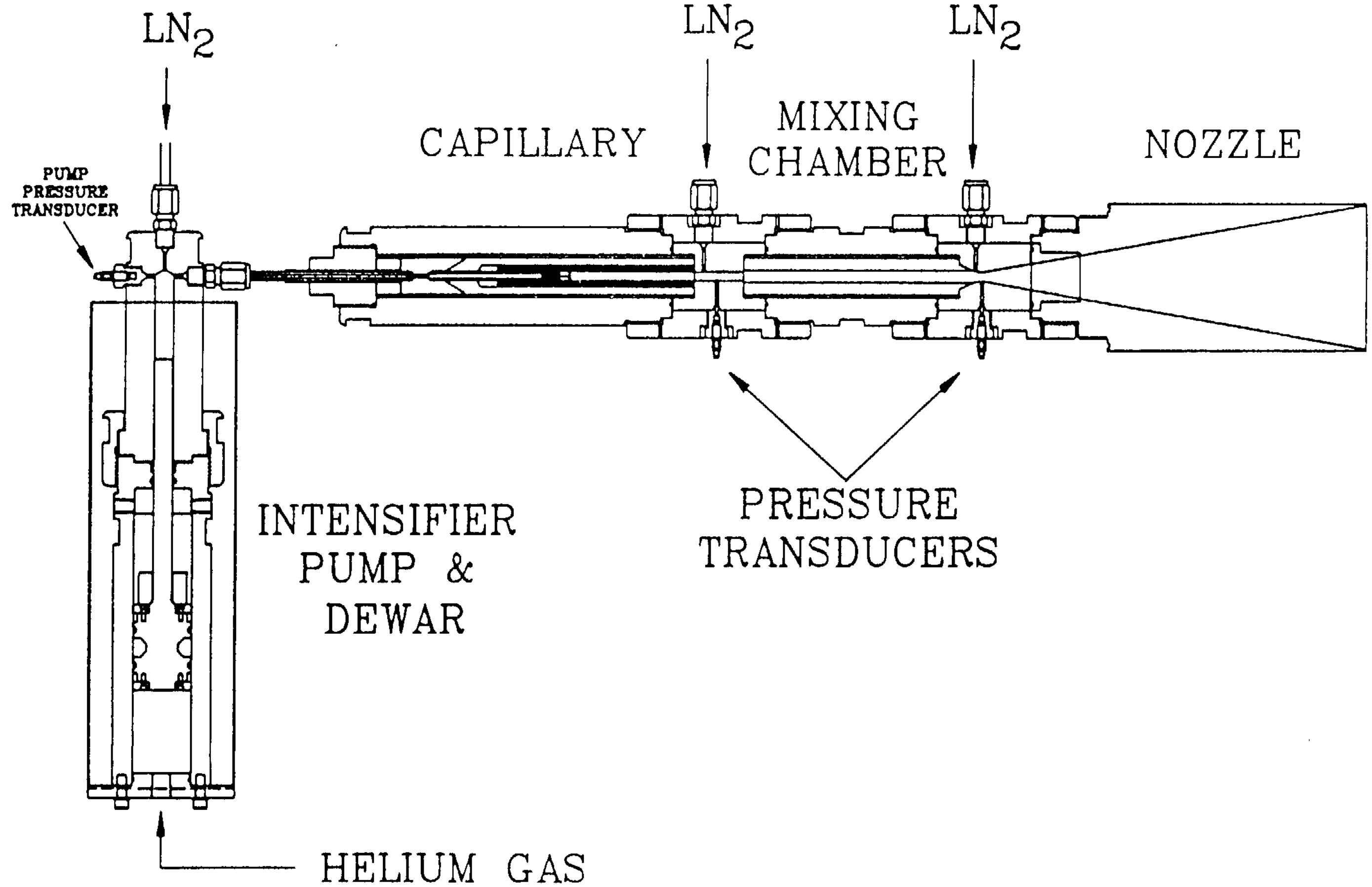


Figure 2. Electrothermal Wind Tunnel.

WT15

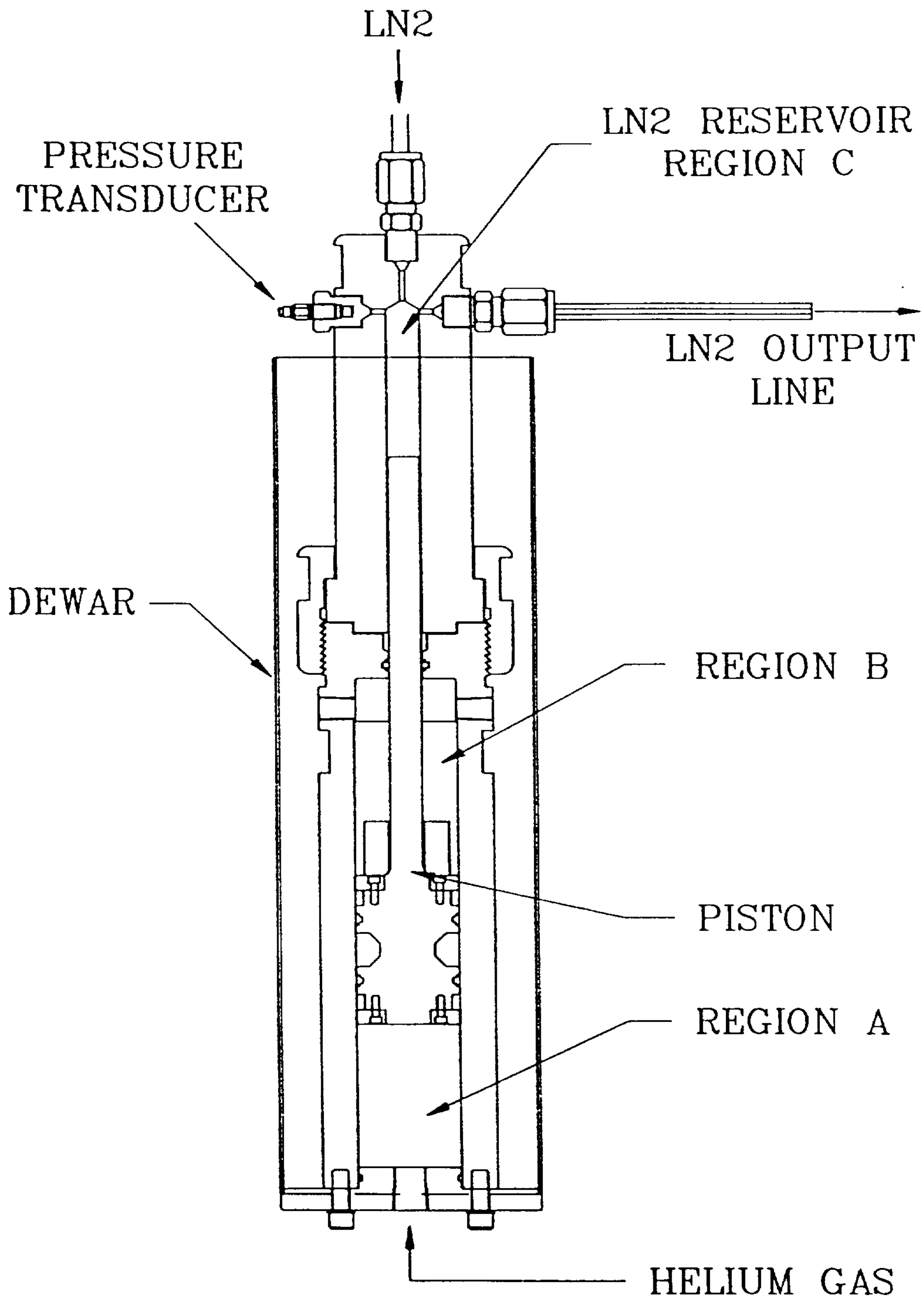
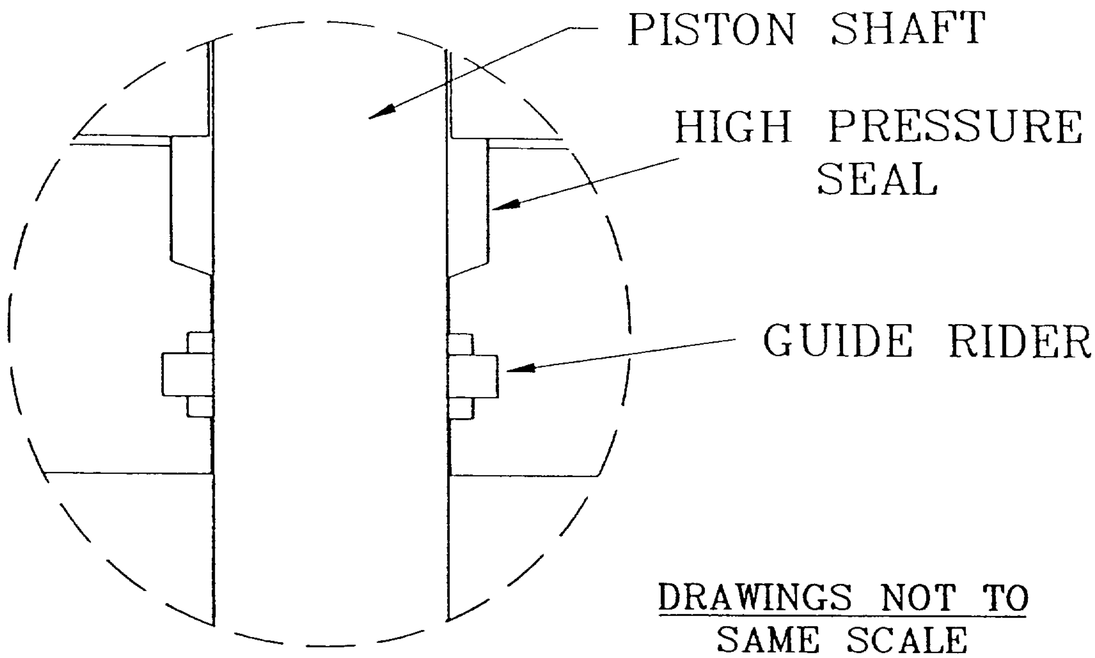


Figure 3. Cryogenic pump.

WT03



DRAWINGS NOT TO SAME SCALE

Figure 4.a. High pressure cryogenic seal.

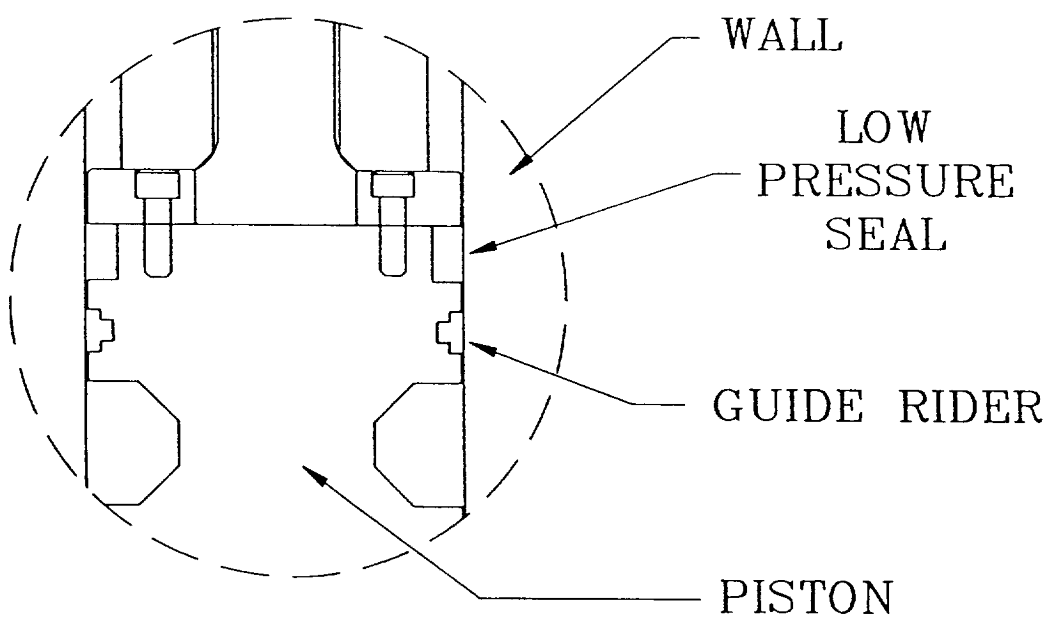


Figure 4.b. Low pressure cryogenic seal.

WT10

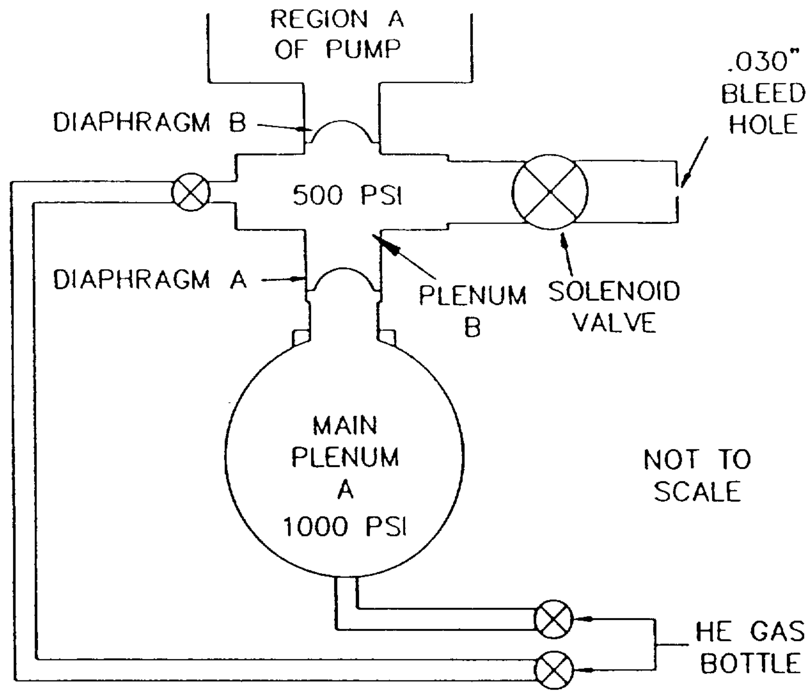


Figure 5.a. Burst diaphragm configuration for operation at room temperature.

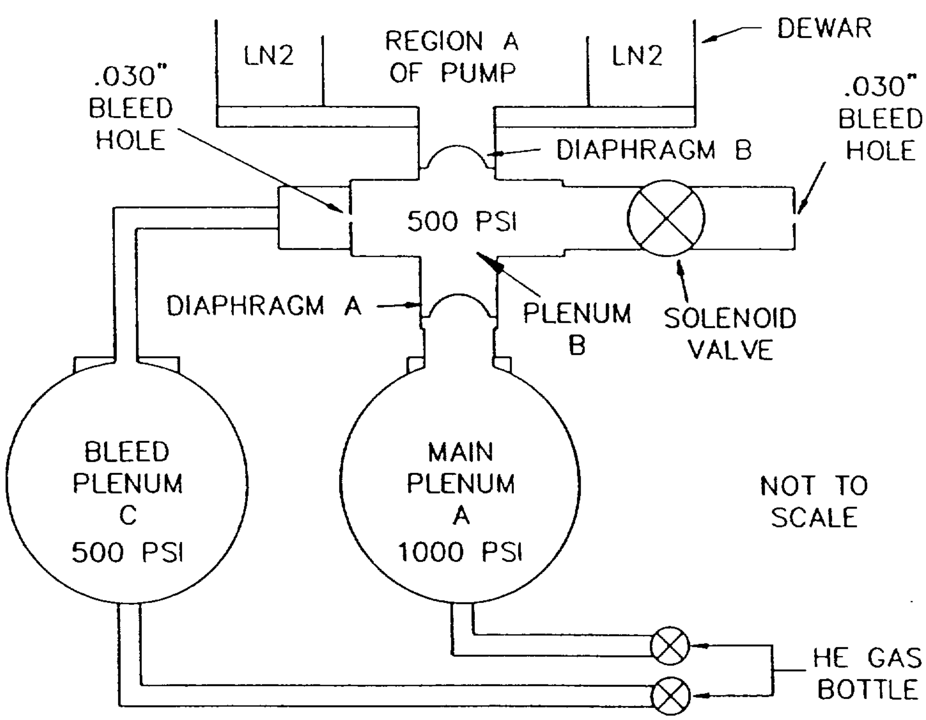


Figure 5.b. Burst diaphragm configuration for operation at cryogenic temperatures.

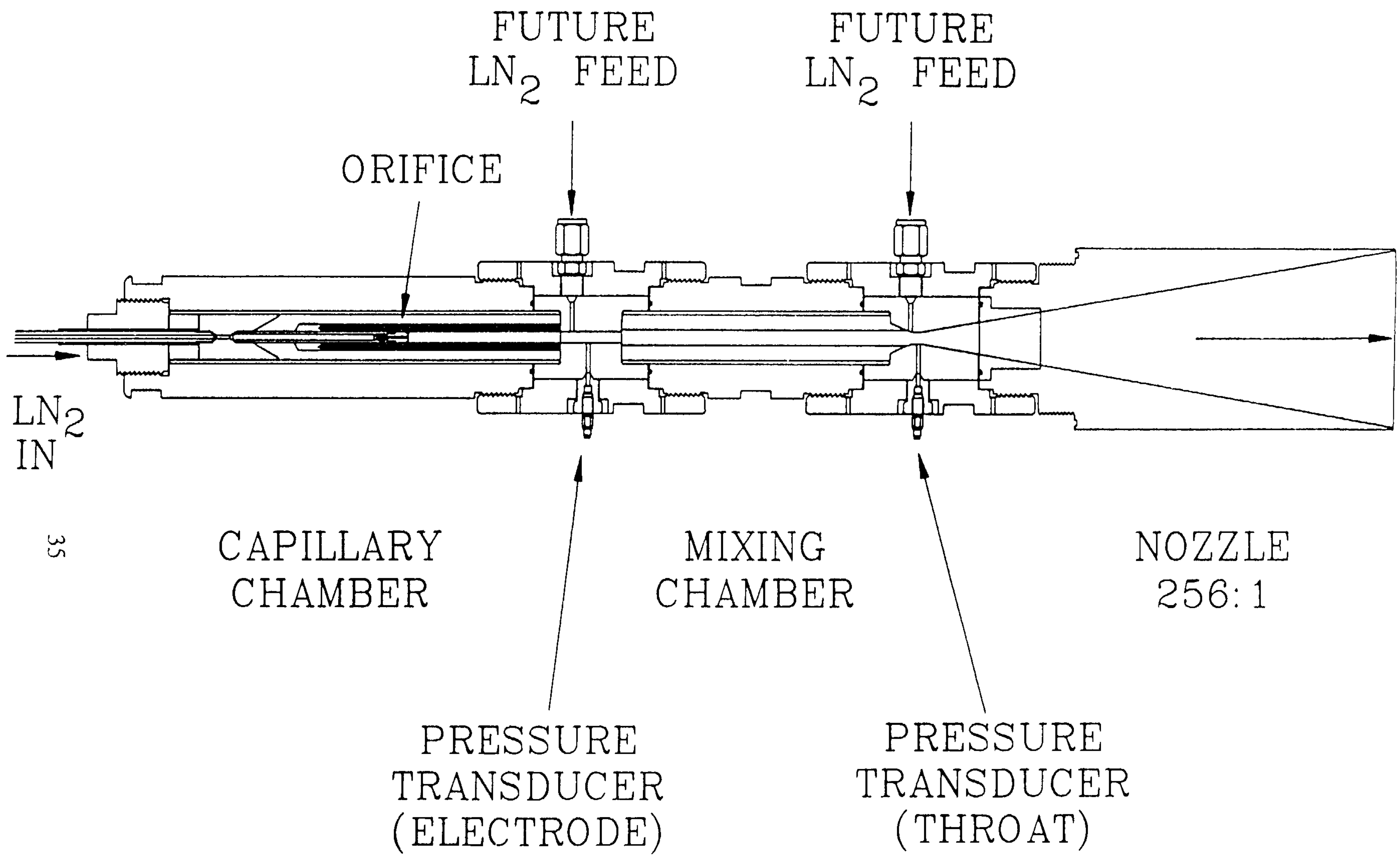


Figure 6. Electrothermal cartridge.

WT04

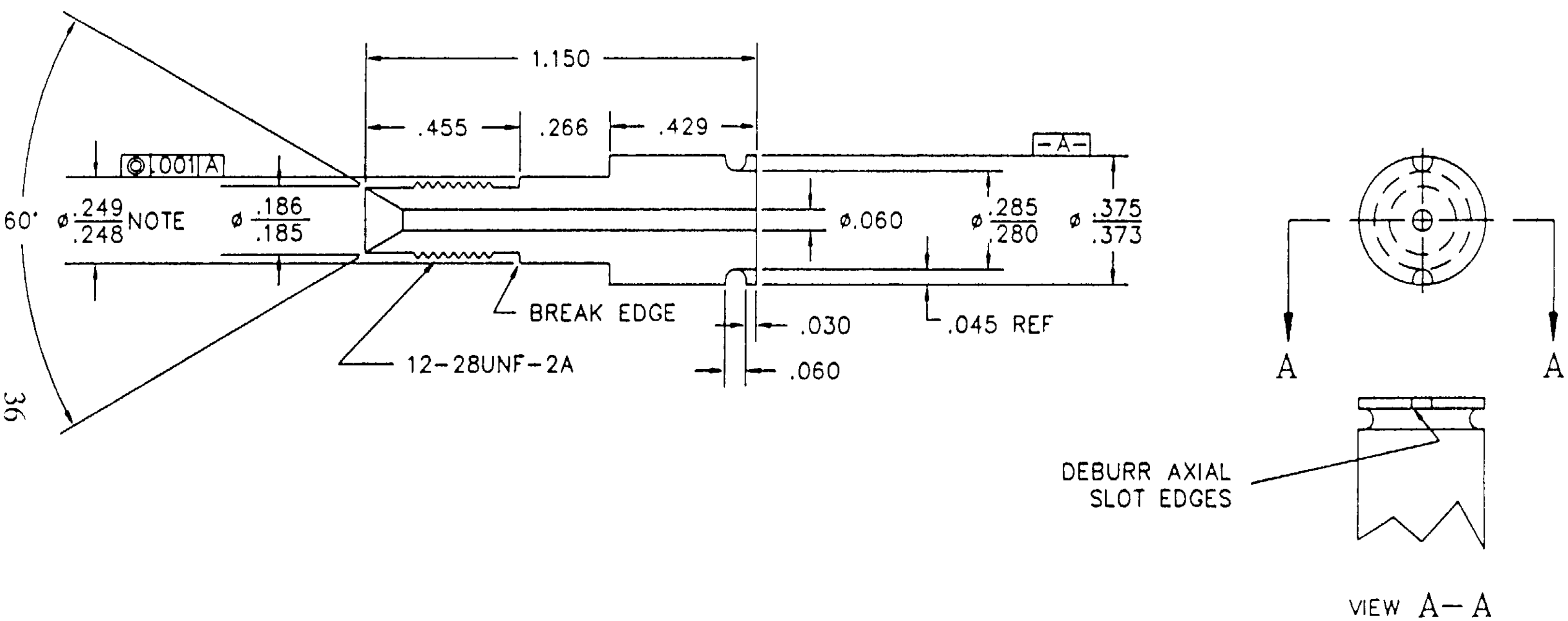


Figure 7. Screw-on electrode tip with integral orifice. Circumferential and axial slots are for attachment of the aluminum foil fuse.

WT13

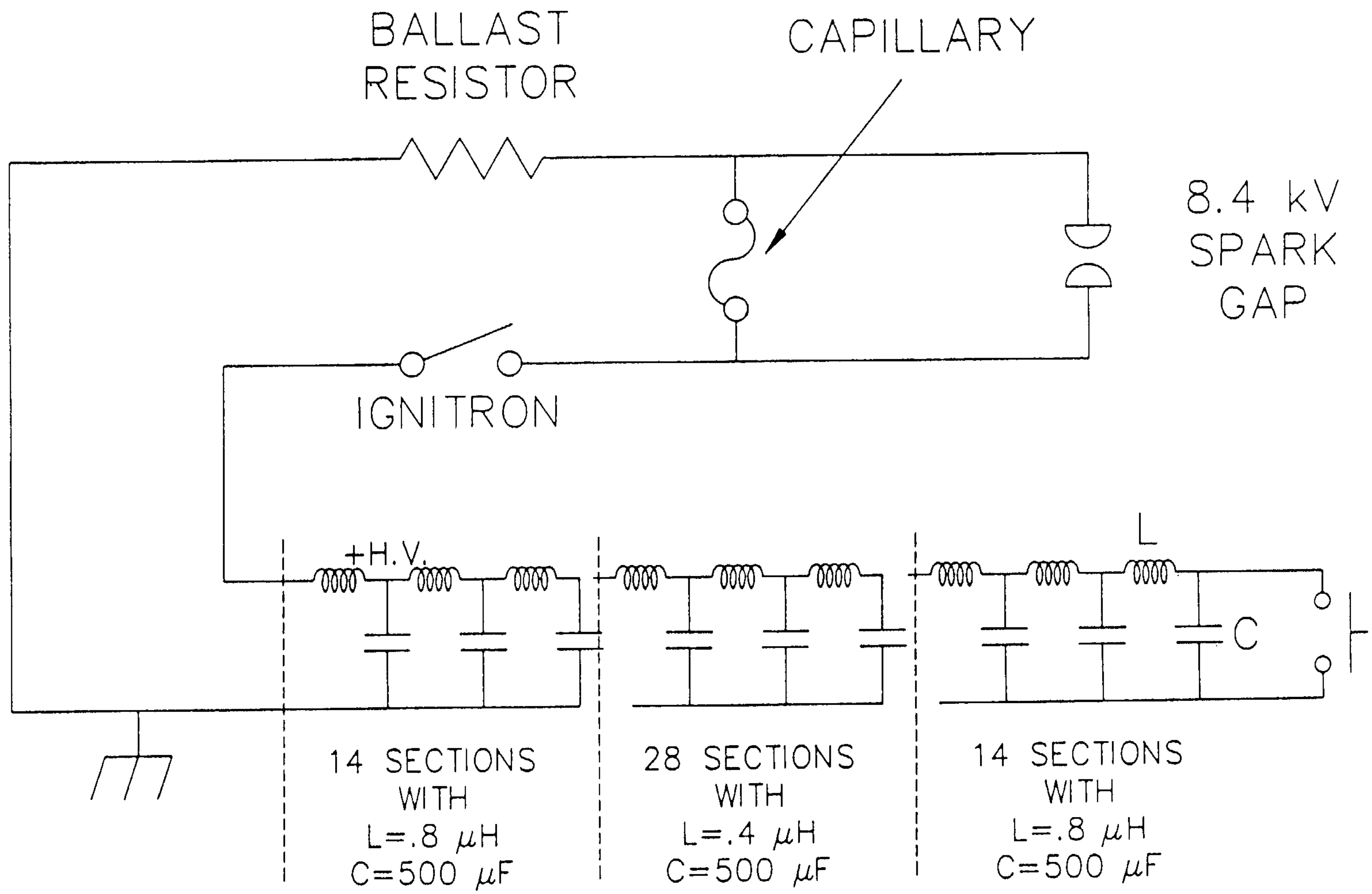


Figure 8. Electrothermal Wind Tunnel high voltage circuit schematic.

WT01

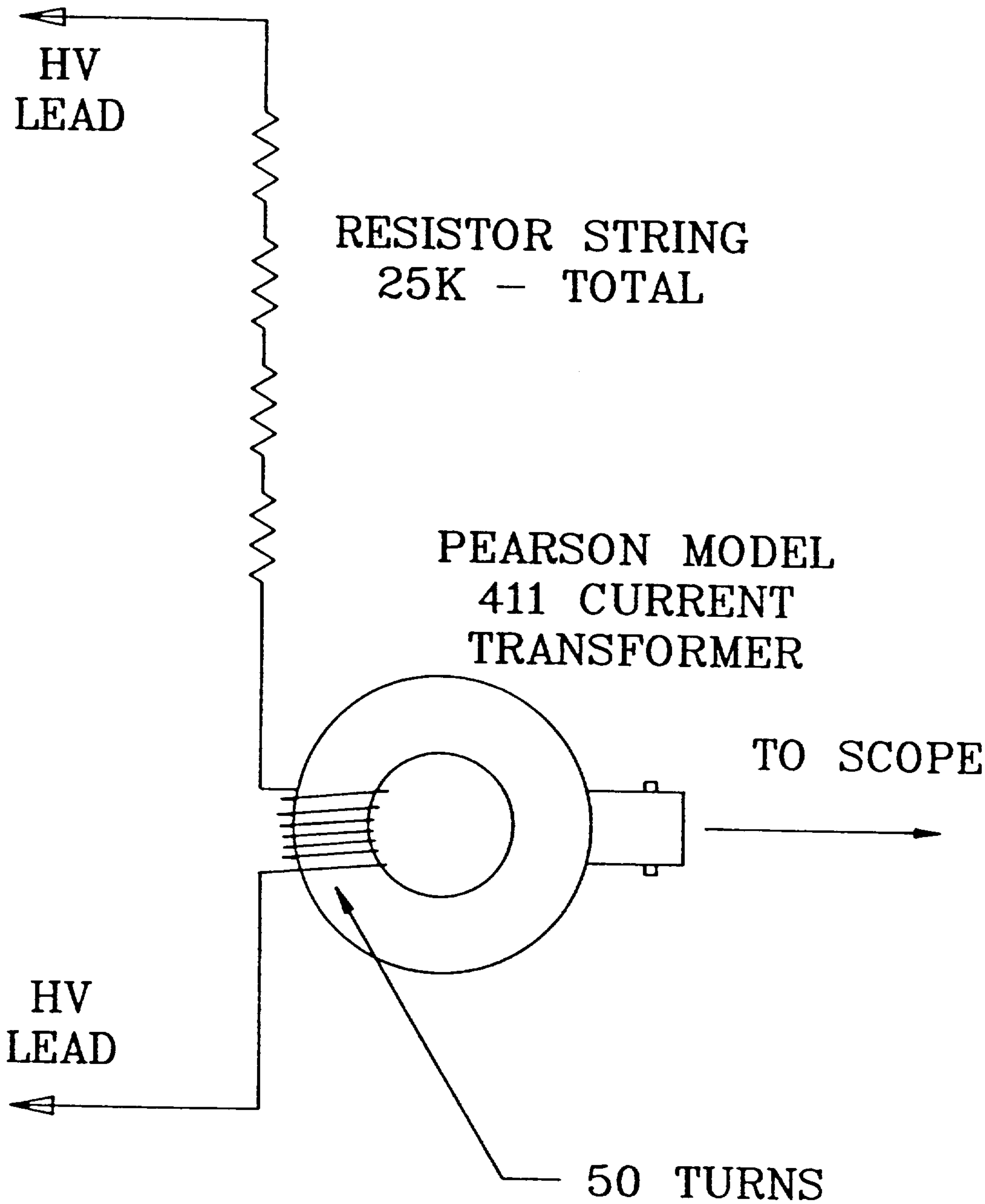


Figure 9. Schematic of differential high voltage probe.

WT02

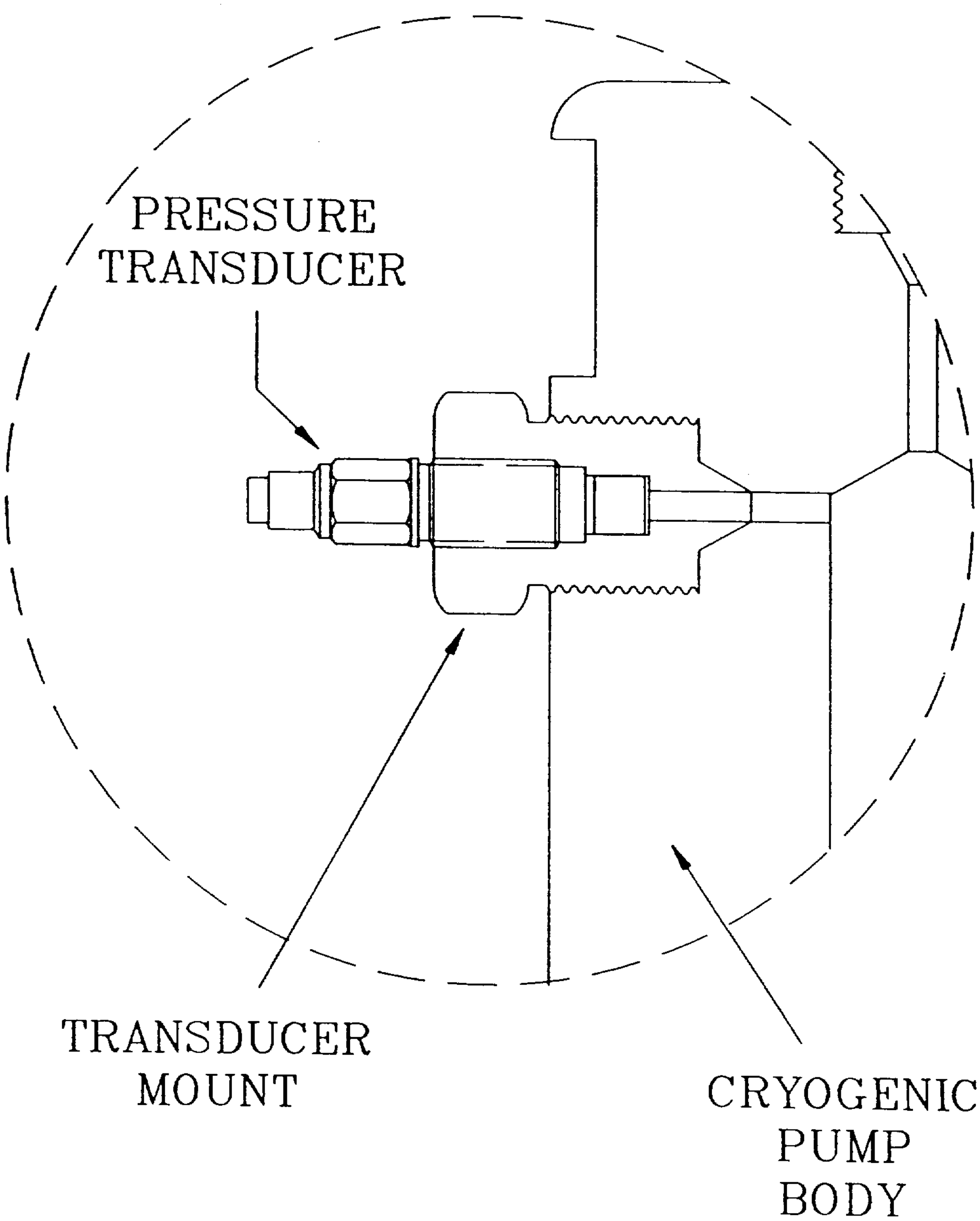


Figure 10. Pressure transducer mount. The same mount design is used both in the cryogenic pump and in the electrothermal cartridge.

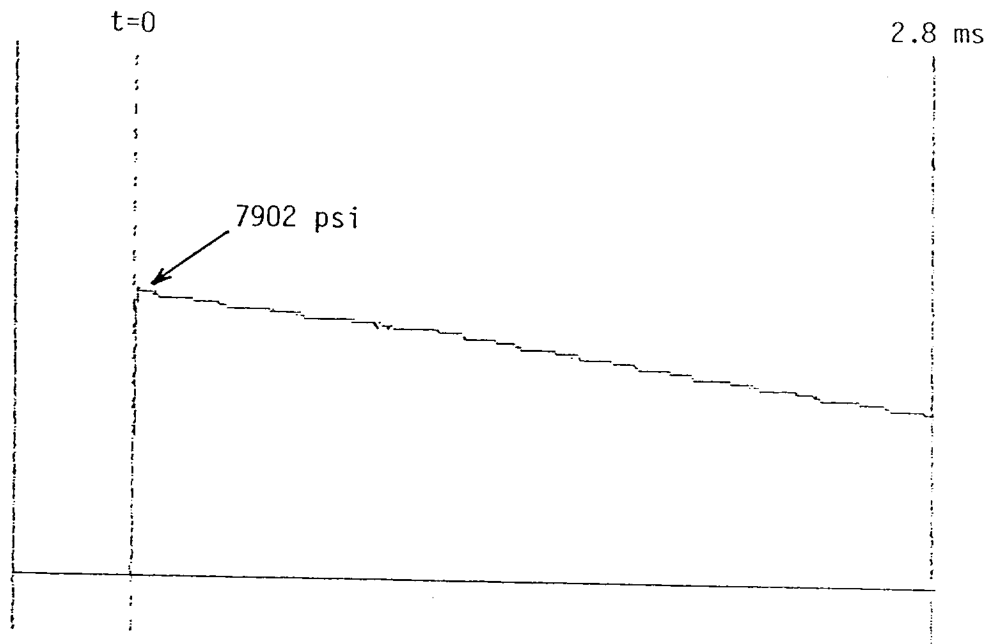


Figure 11. Pressure trace from static pump test using water and burst diaphragms with a plenum pressure of 850 psi.

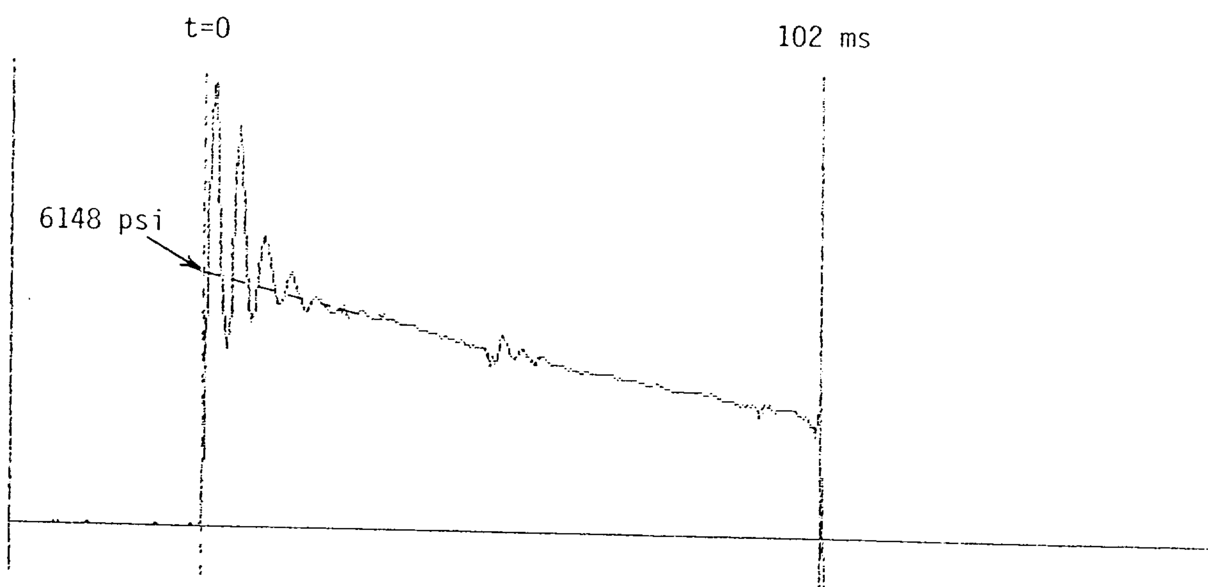


Figure 12. Pressure trace from dynamic pump test with water and burst diaphragms. Plenum pressure is 900 psi.

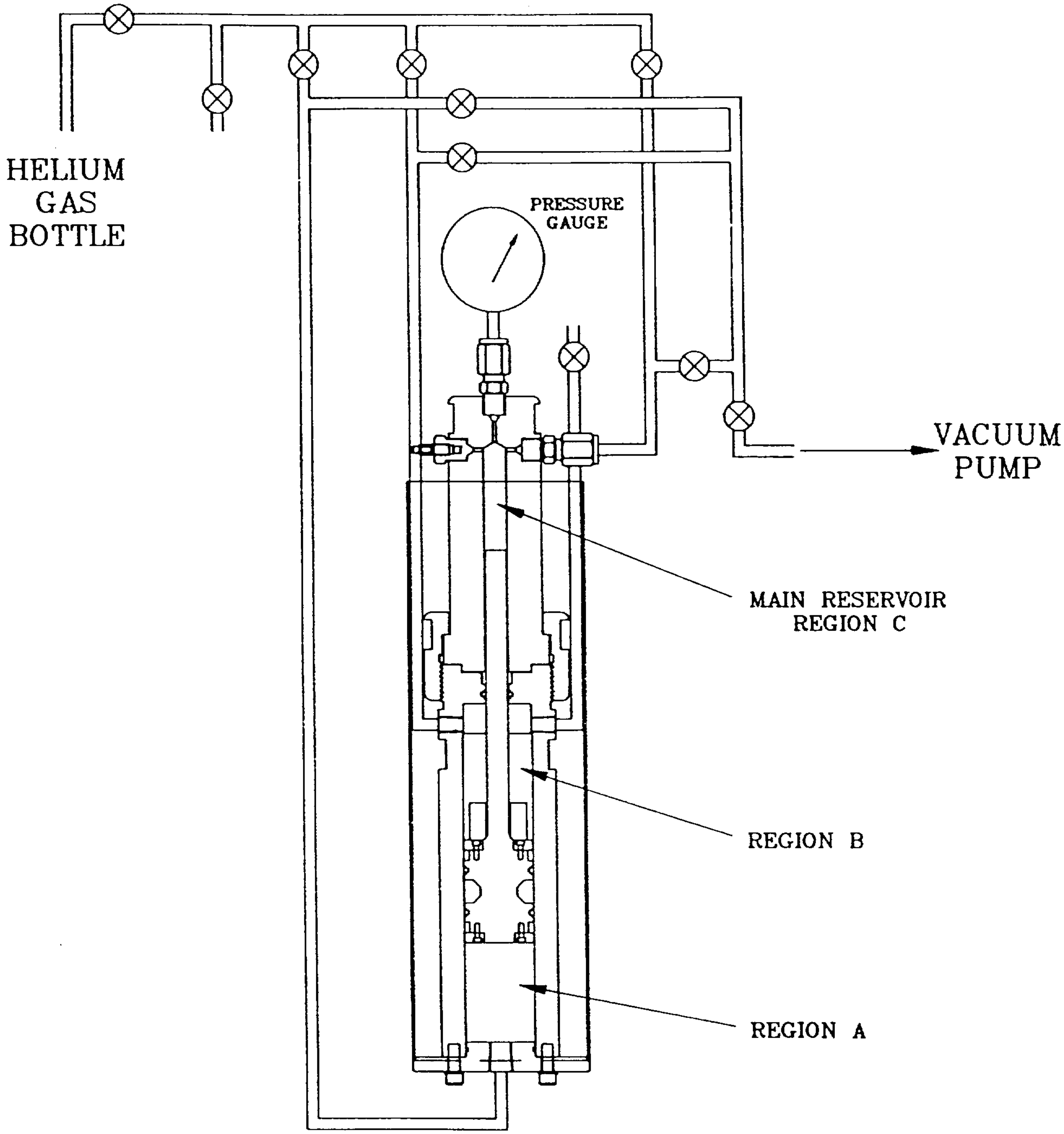


Figure 13.a. Schematic of cryogenic pump showing external plumbing and valves used to eliminate water vapor in free piston tests.

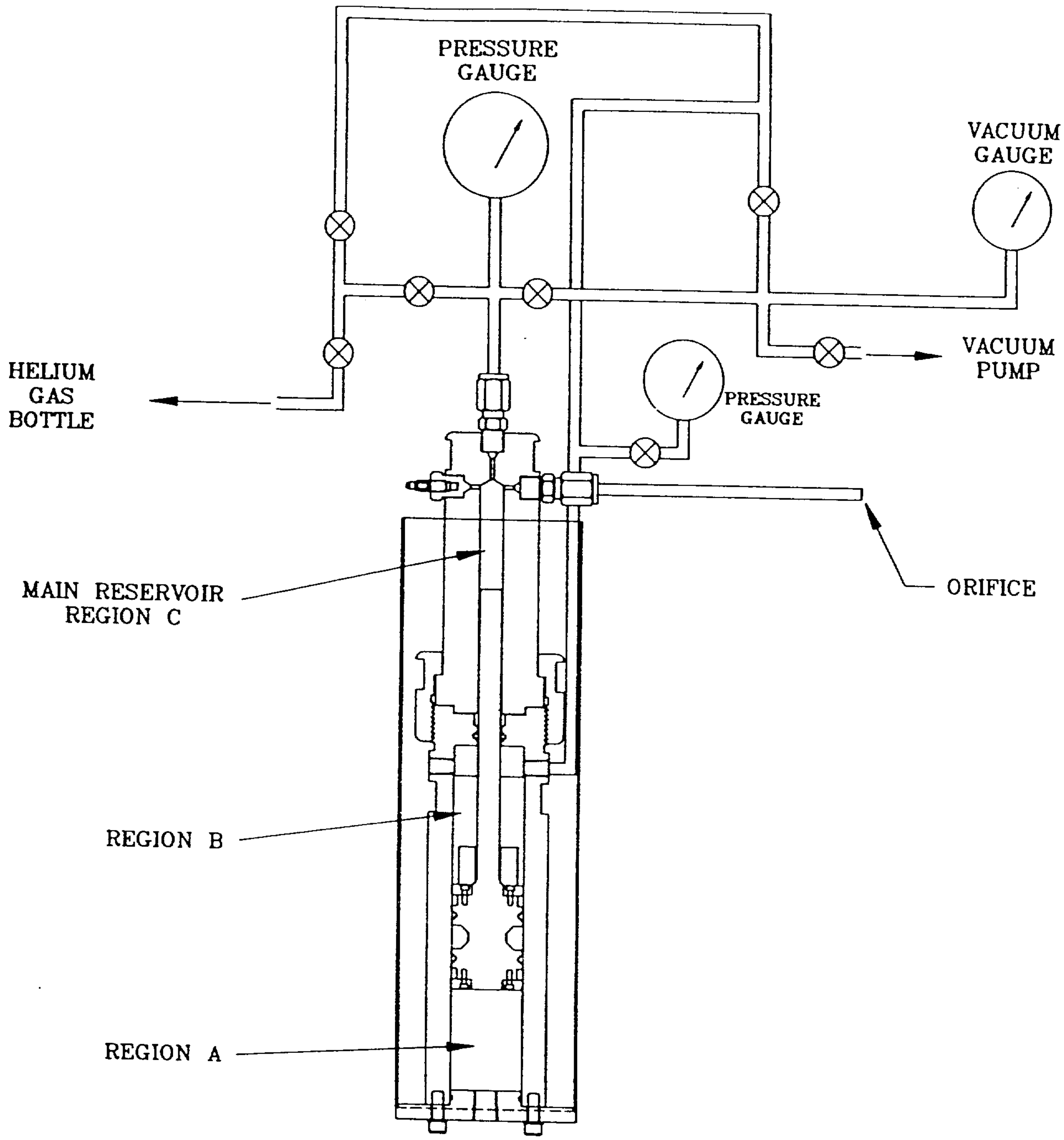


Figure 13.b. Schematic of cryogenic pump showing external plumbing, valves, and gauges used for full wind tunnel tests. Most of the plumbing is removed once main reservoir is filled with LN_2 just prior to shot.

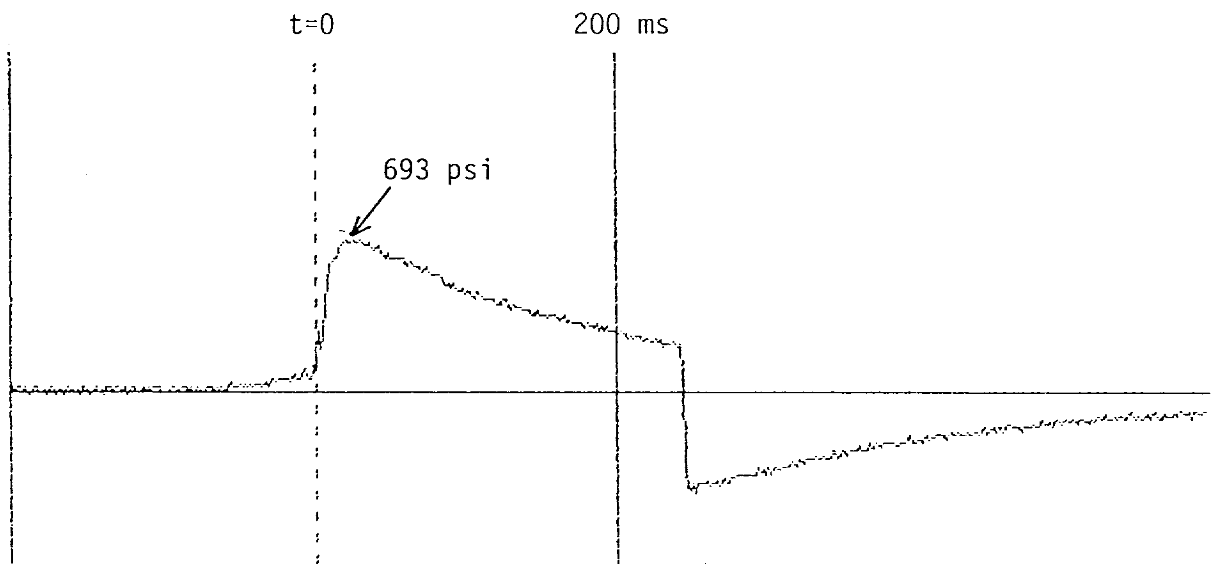
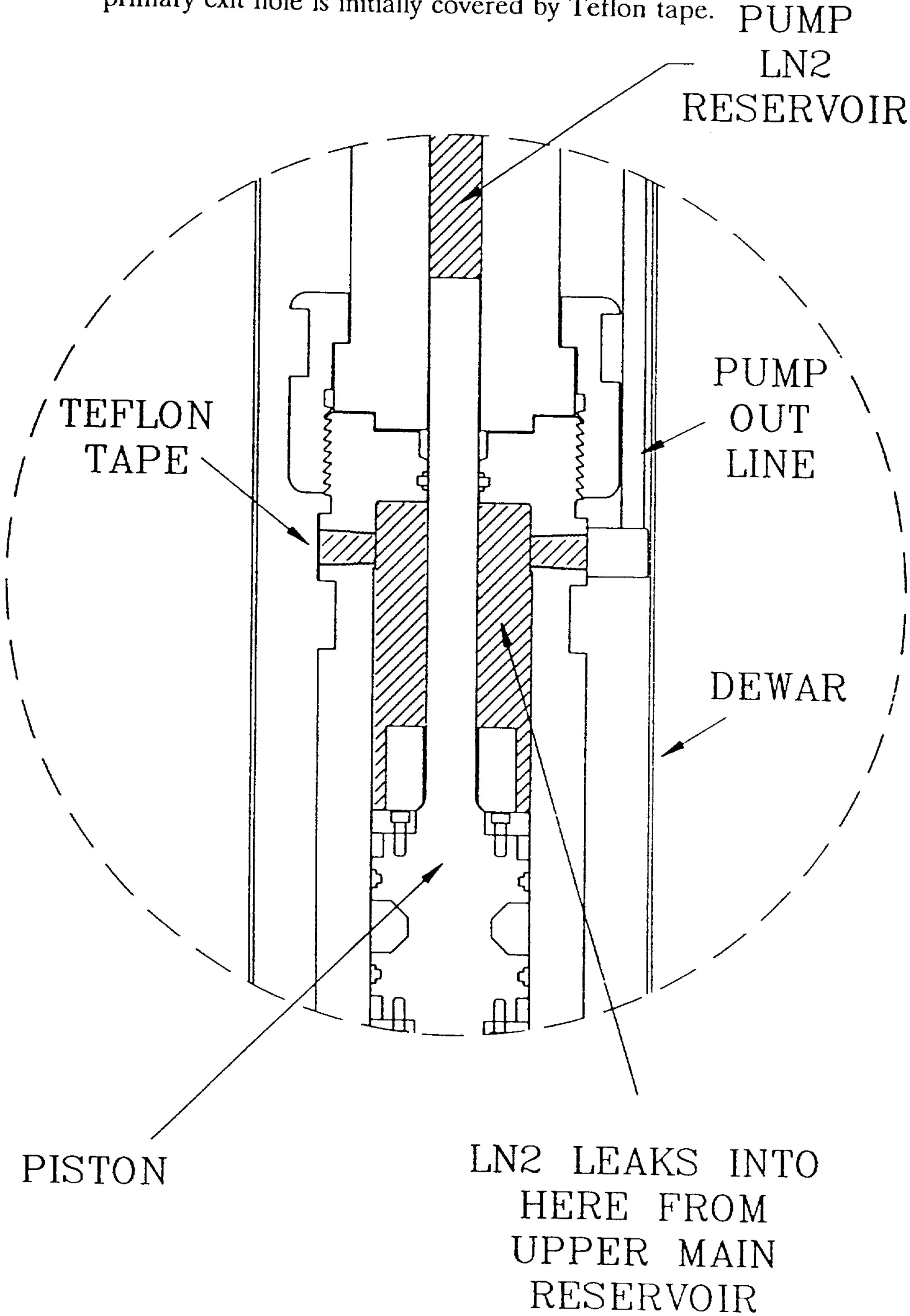


Figure 14. Pump pressure from Shot 11.

Figure 15. Internal pump configuration showing LN_2 leakage from main reservoir, Region C, into Region B. Retardation of piston motion is alleviated by providing two exit holes through which LN_2 can be pumped with low pressure drop. The primary exit hole is initially covered by Teflon tape.



WT09

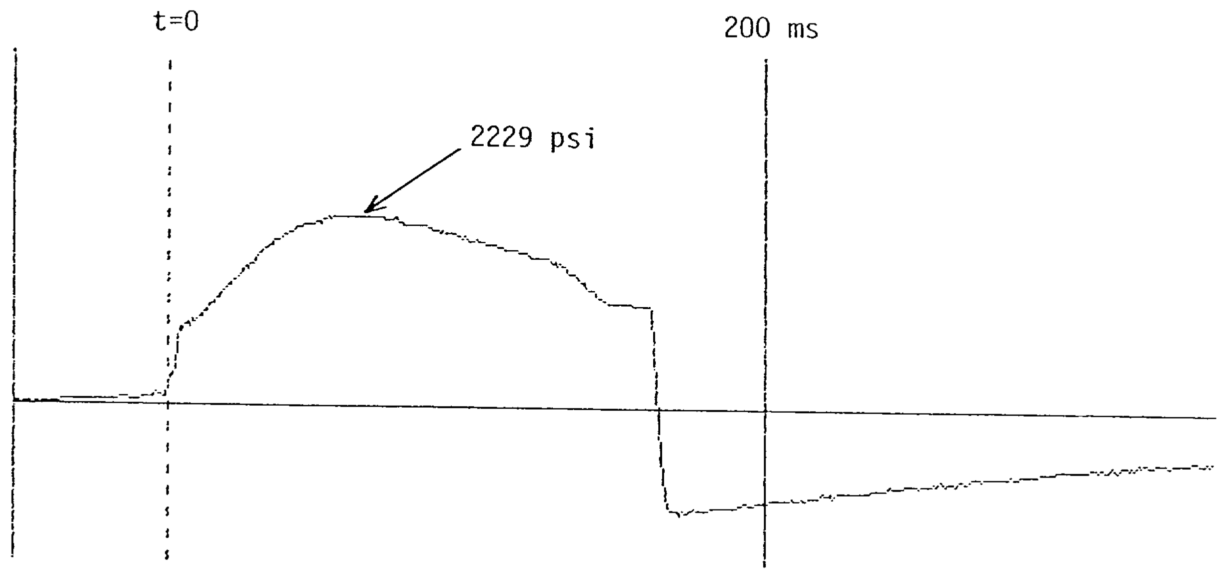


Figure 16. Pump pressure from Shot 12. Plenum pressure is 500 psi.

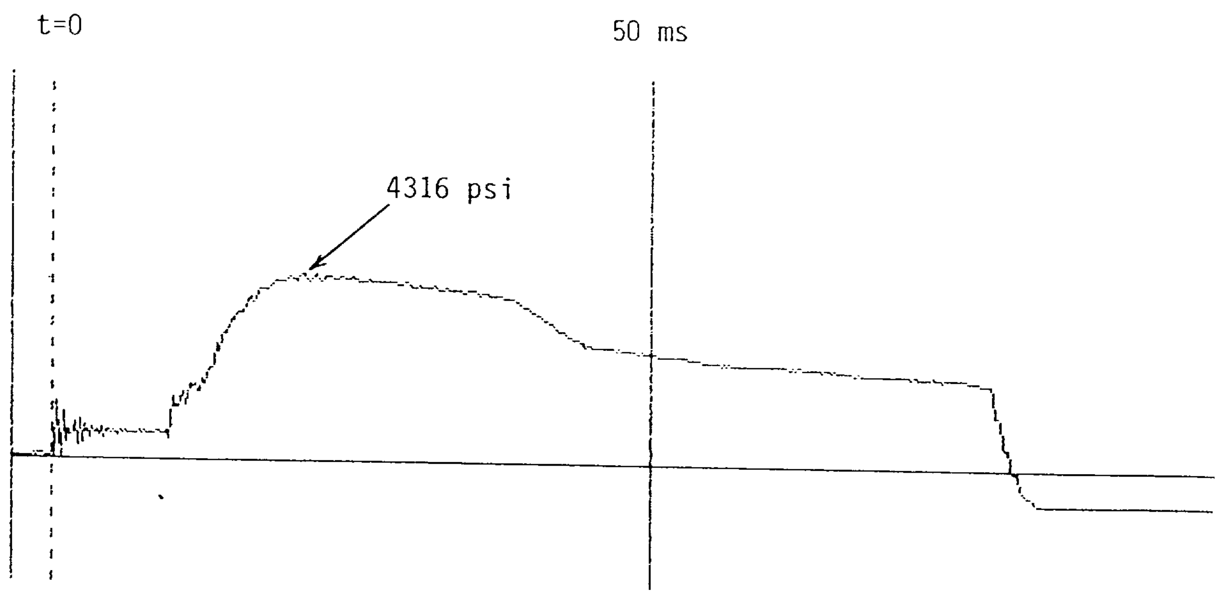


Figure 17. Pump pressure for Shot 13. Plenum pressure is 875 psi.

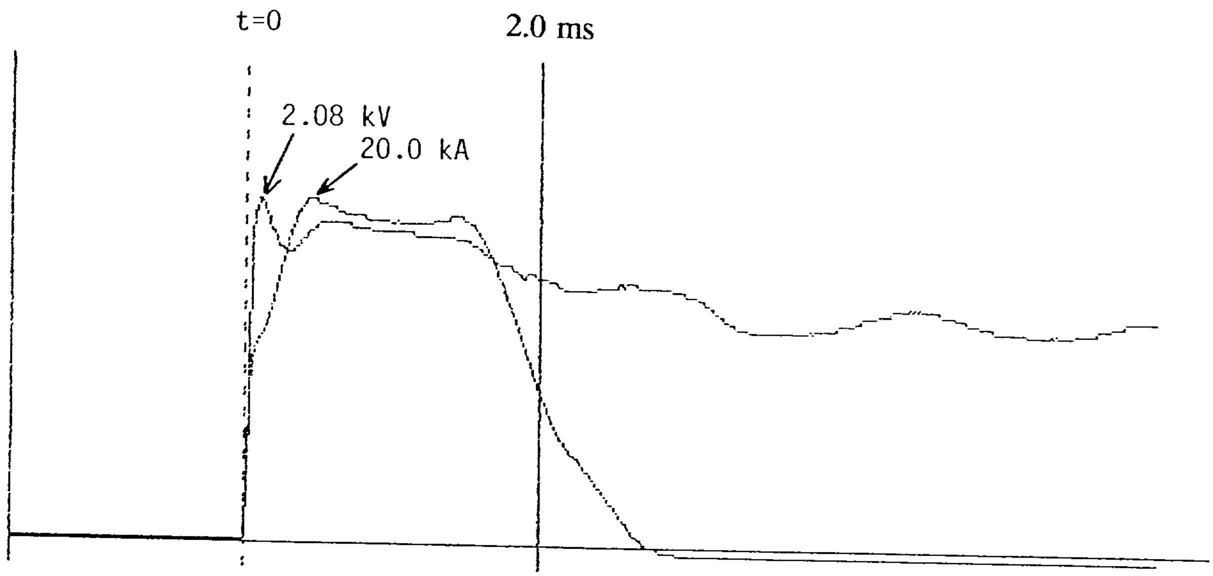


Figure 18. Current and voltage from Shot 4. This is a baseline "hot" shot with no liquid injection.

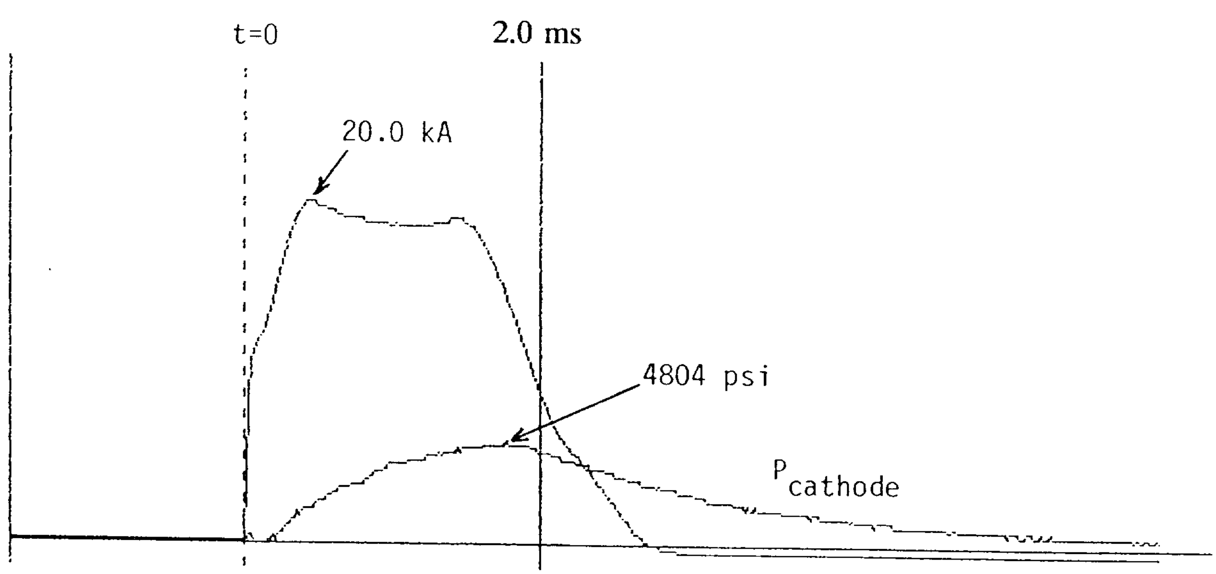


Figure 19. Pressure at capillary exit electrode for Shot 4. Current is shown for reference.

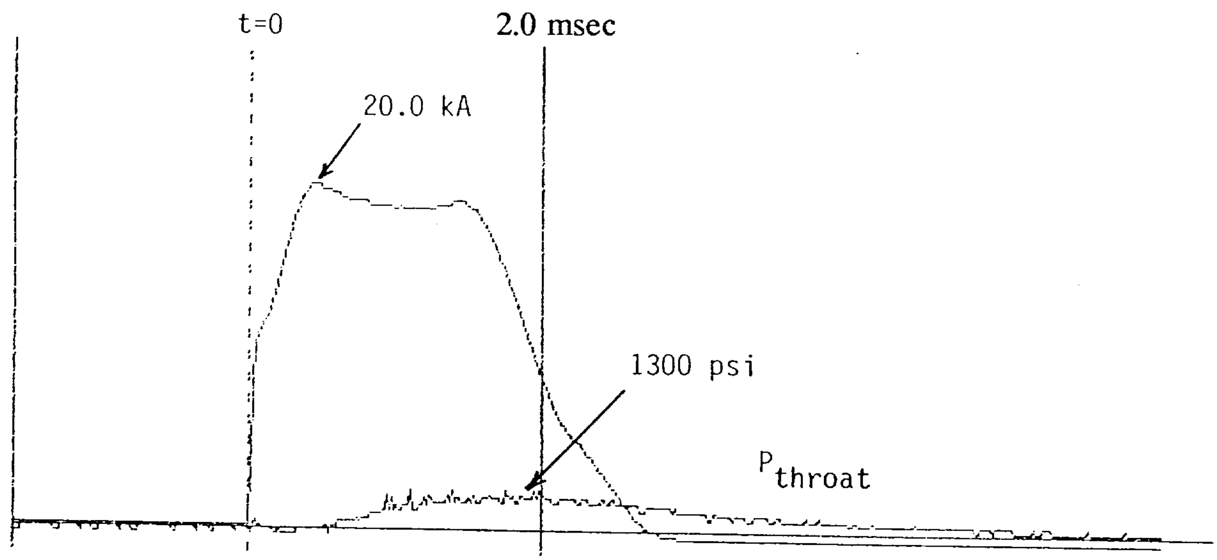


Figure 20. Pressure at nozzle throat for Shot 4. Current is shown for reference.

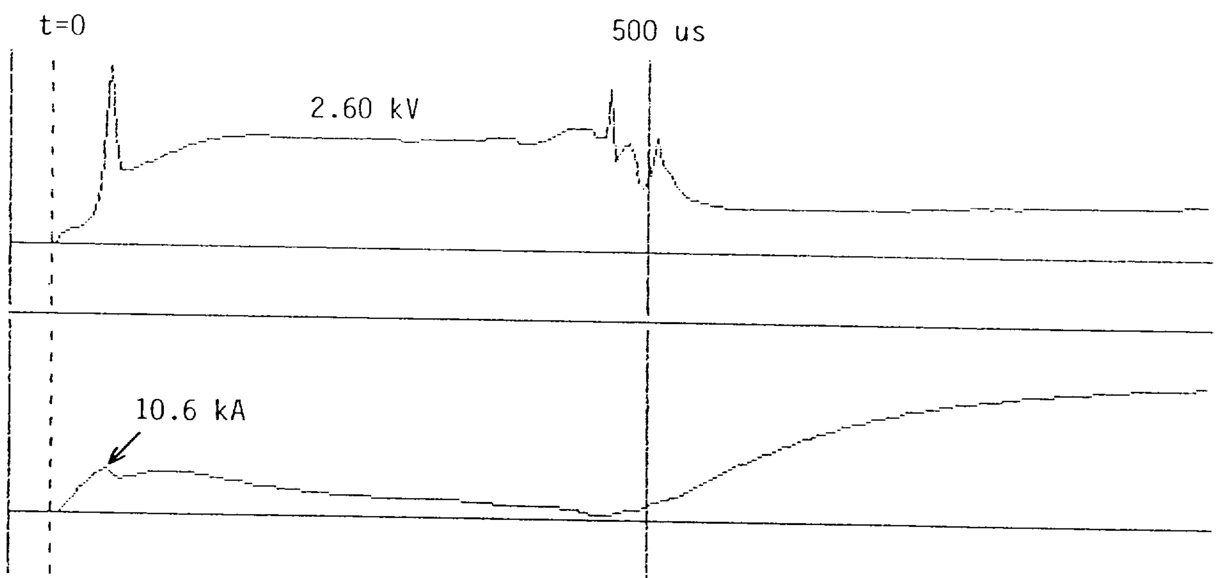


Figure 21. Current and voltage from Shot 3 in which current is quenched and then followed by external arc over resulting from insulation failure.

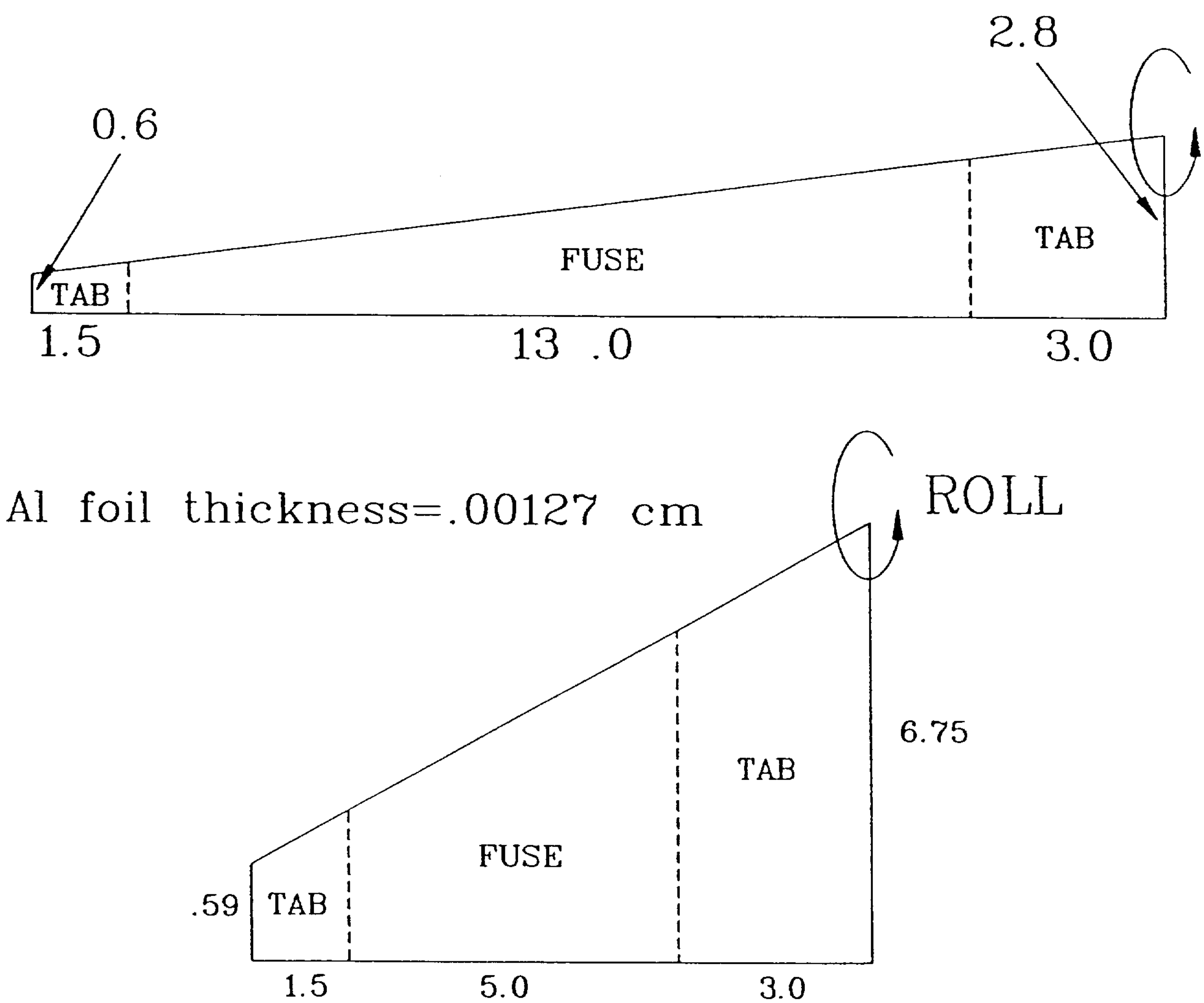


Figure 22. Fuse designs for 13 cm capillary (upper) and for 5 cm capillary (lower). Dimensions shown are in centimeters.

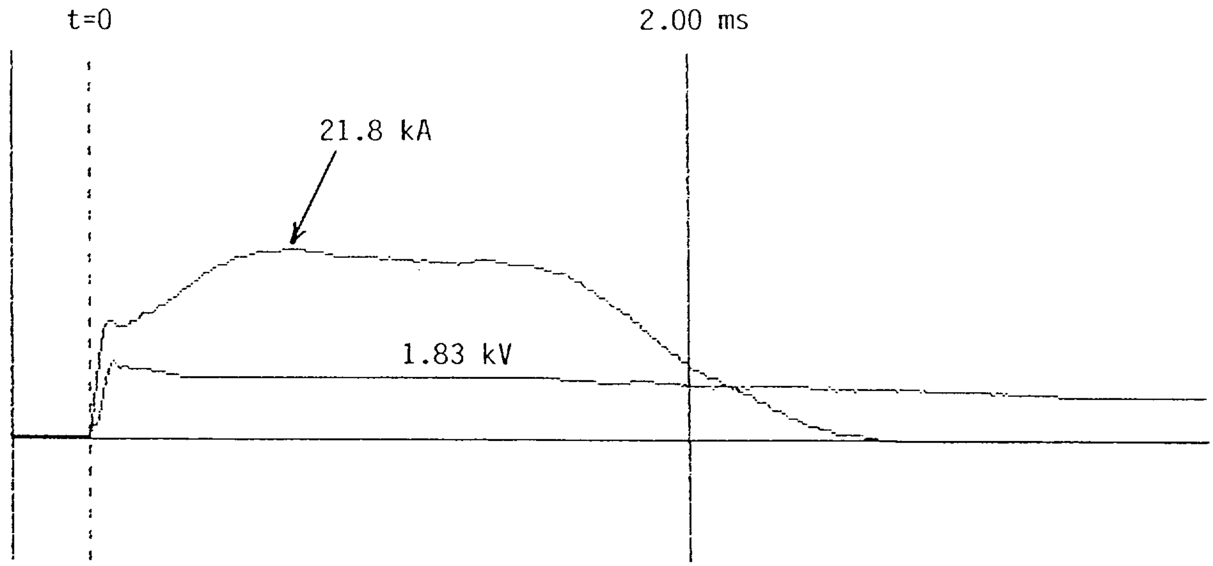


Figure 23. Current and voltage from Shot 8.

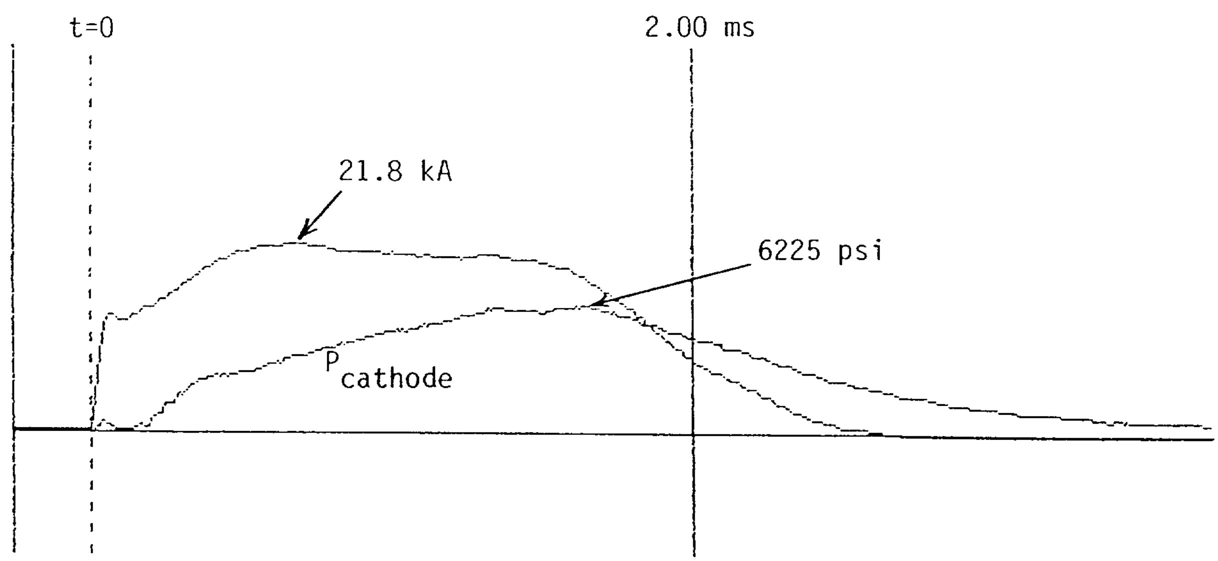


Figure 24. Pressure at capillary exit electrode for Shot 8. Current is shown for reference.

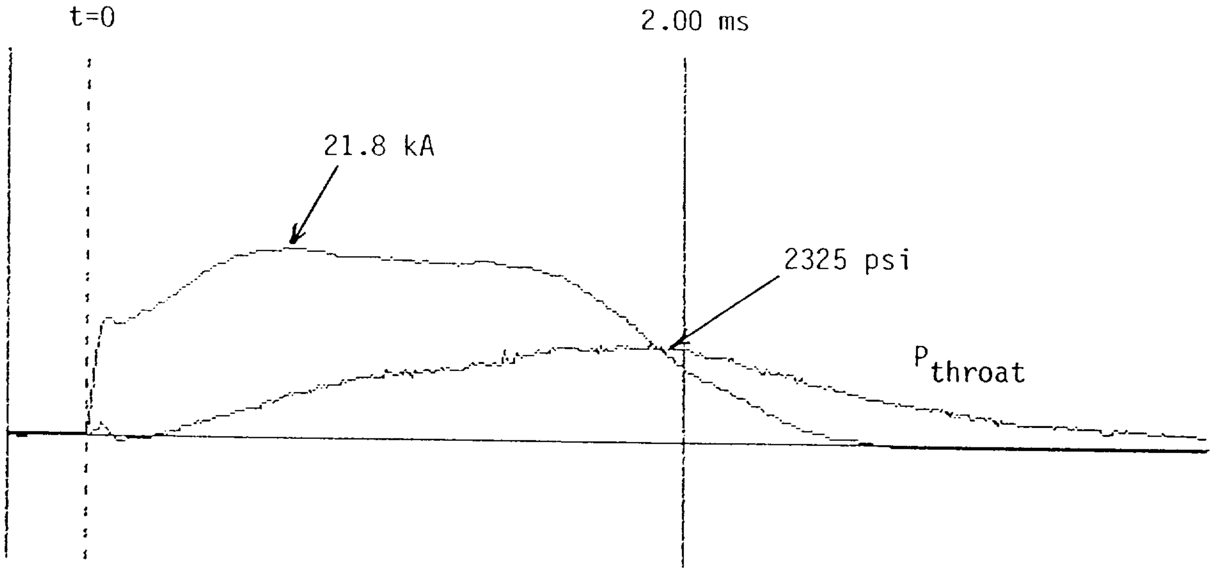


Figure 25. Pressure at nozzle throat for Shot 8. Current is shown for reference.

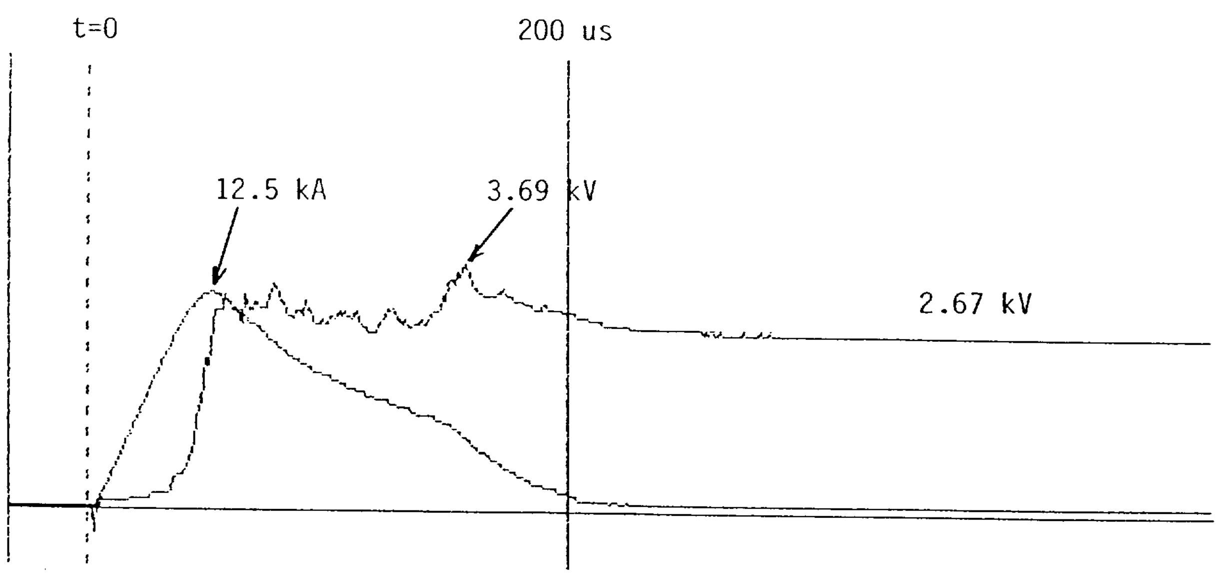


Figure 26. Current and voltage from quenched discharge on Shot 14 with LN_2 injection.

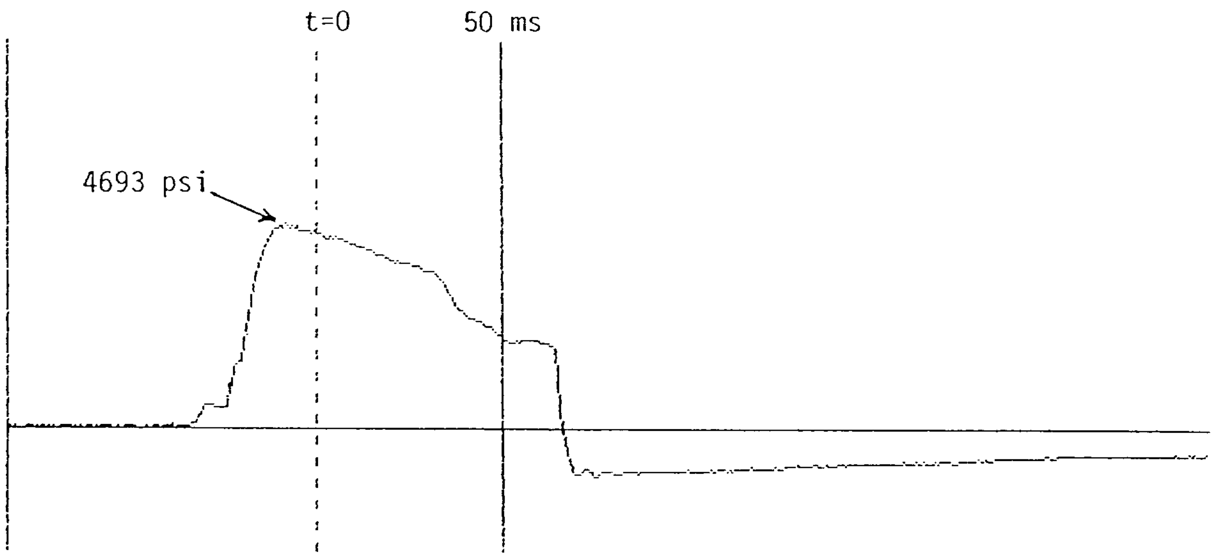


Figure 27. Pump pressure from Shot 14 with LN_2.

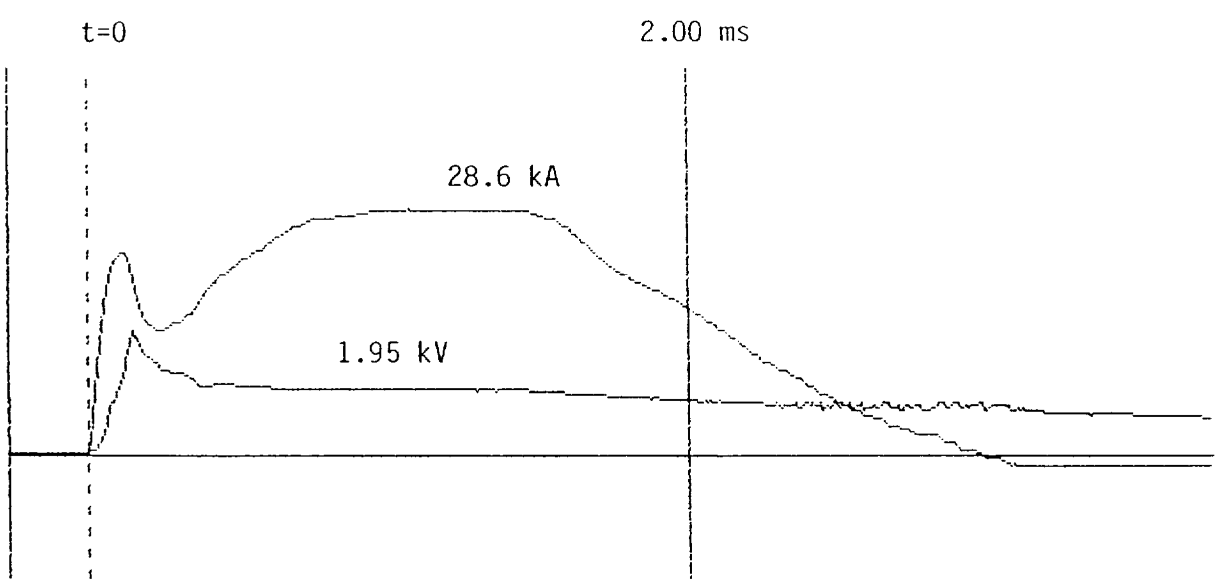


Figure 28. Current and voltage from Shot 18.

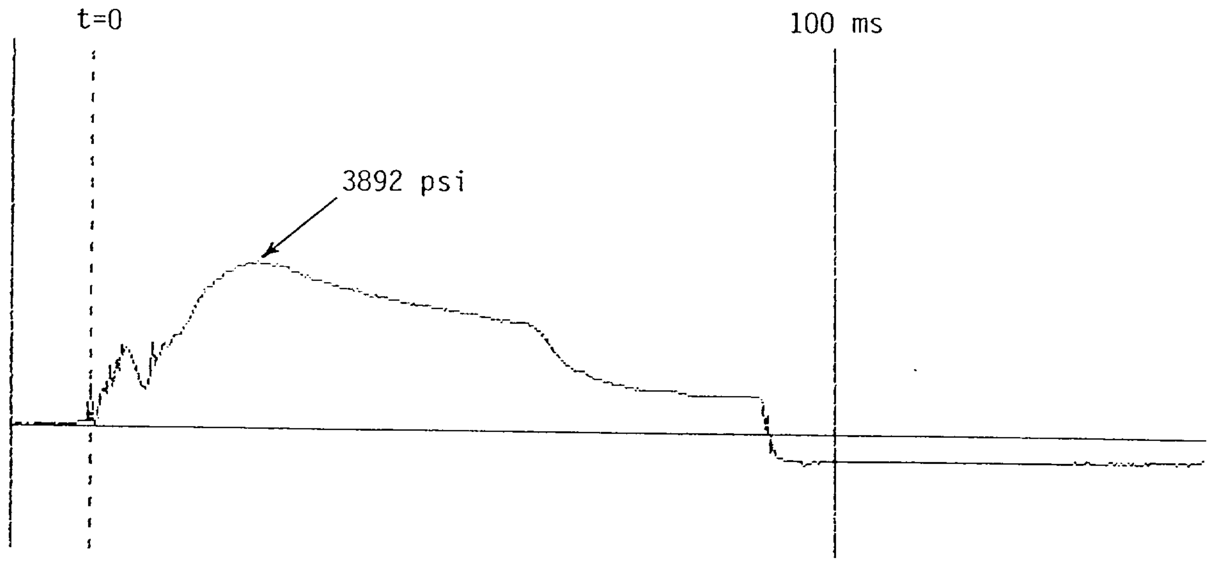


Figure 29. Pump pressure from Shot 18 with LN_2.

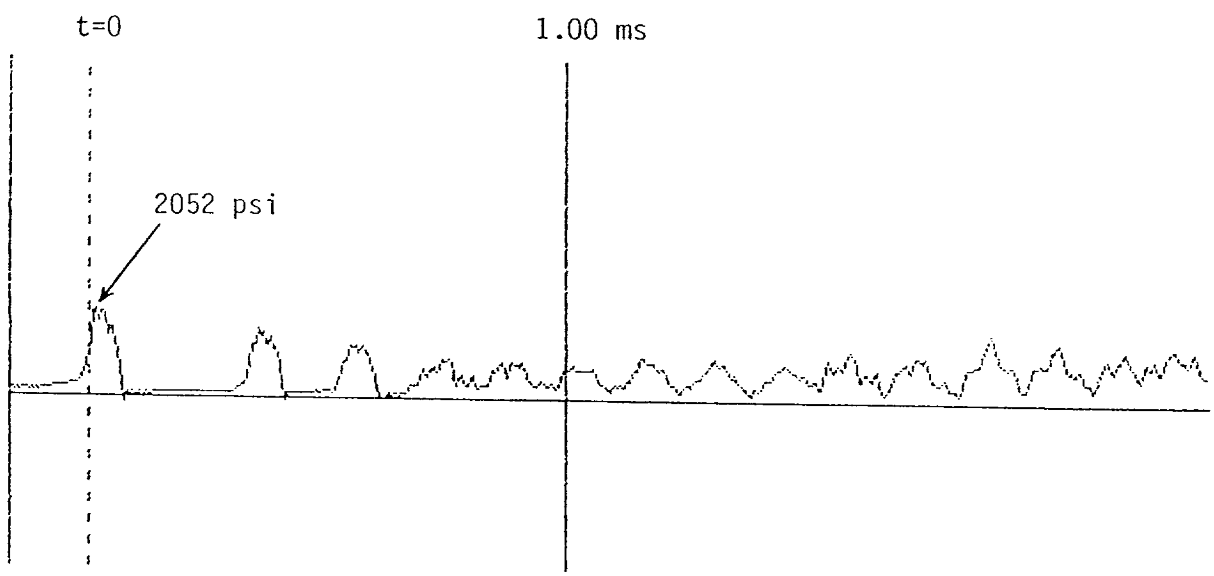


Figure 30. Pump pressure from Shot 18 expanded in time to show pressure pulses just after trigger receipt.

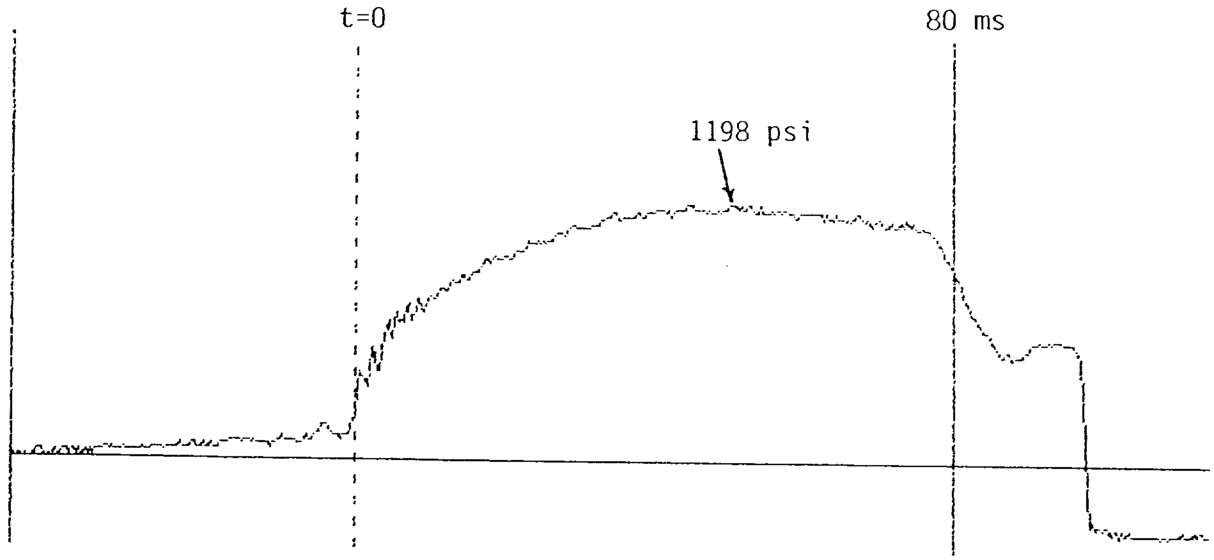


Figure 31. Pump pressure from Shot 20 with LN_2. Pump is actuated with a manually operated plug valve rather than burst diaphragms to eliminate pressure pulses.

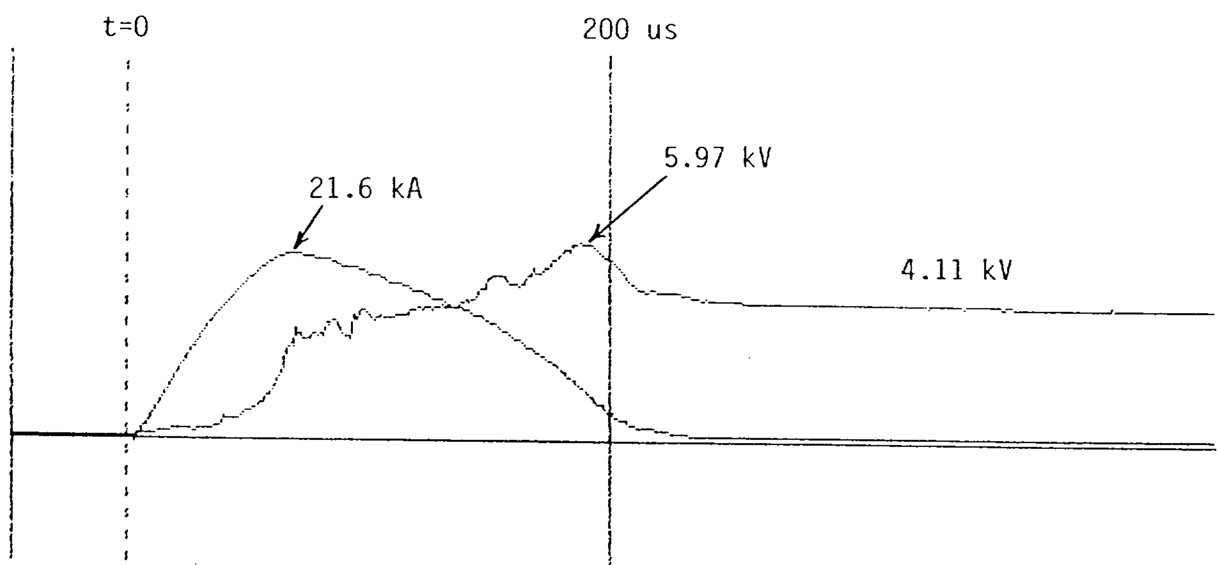


Figure 32. Current and voltage from Shot 21 with LN_2. Discharge was successfully triggered at correct time but discharge quenched.

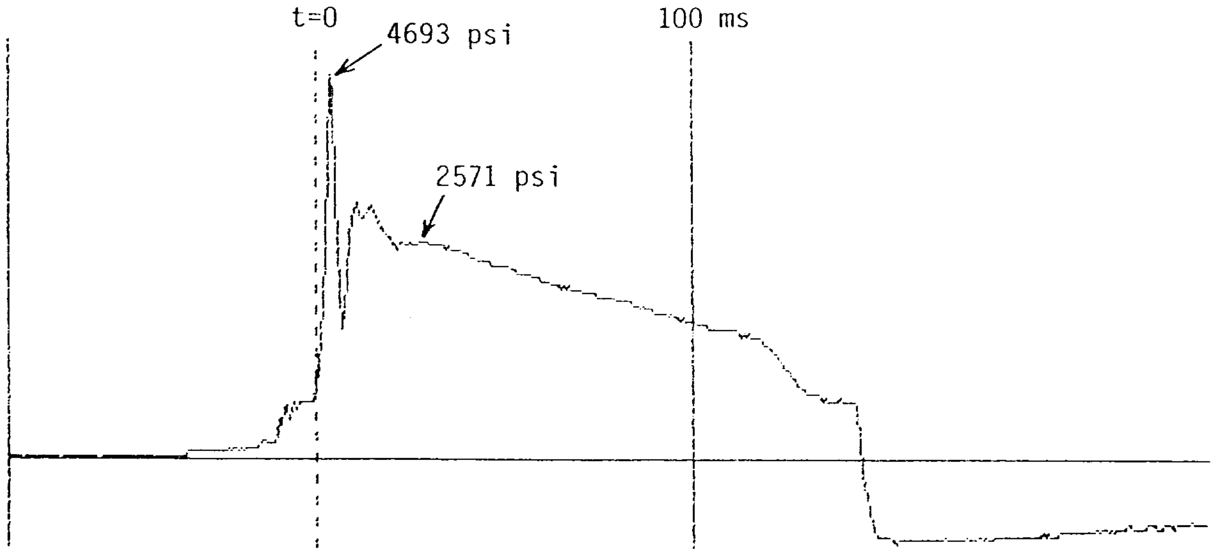


Figure 33. Pump pressure from Shot 22 with LN_2 and successful capillary discharge.

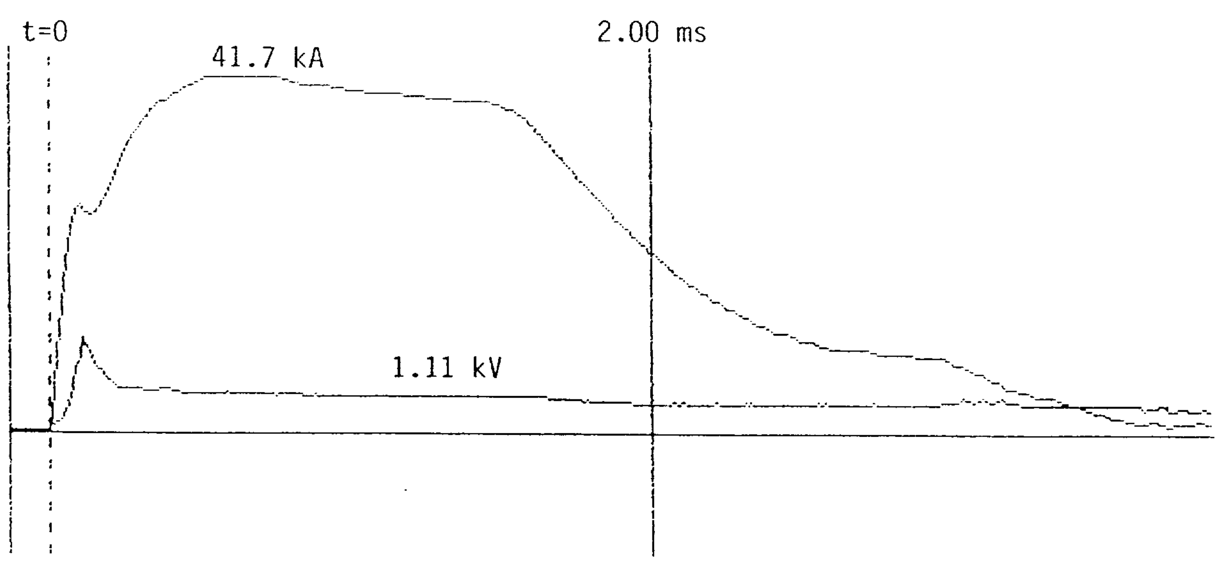


Figure 34. Current and voltage from Shot 22. Capillary length was reduced to 5 cm to eliminate current quenching.

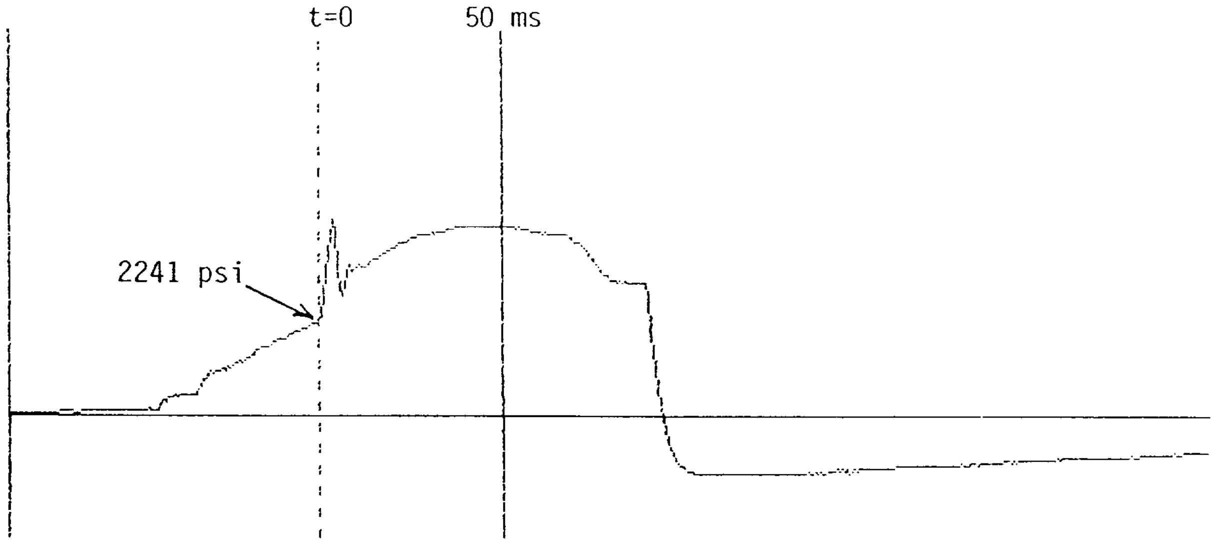


Figure 35. Pump pressure from Shot 23 with LN_2.

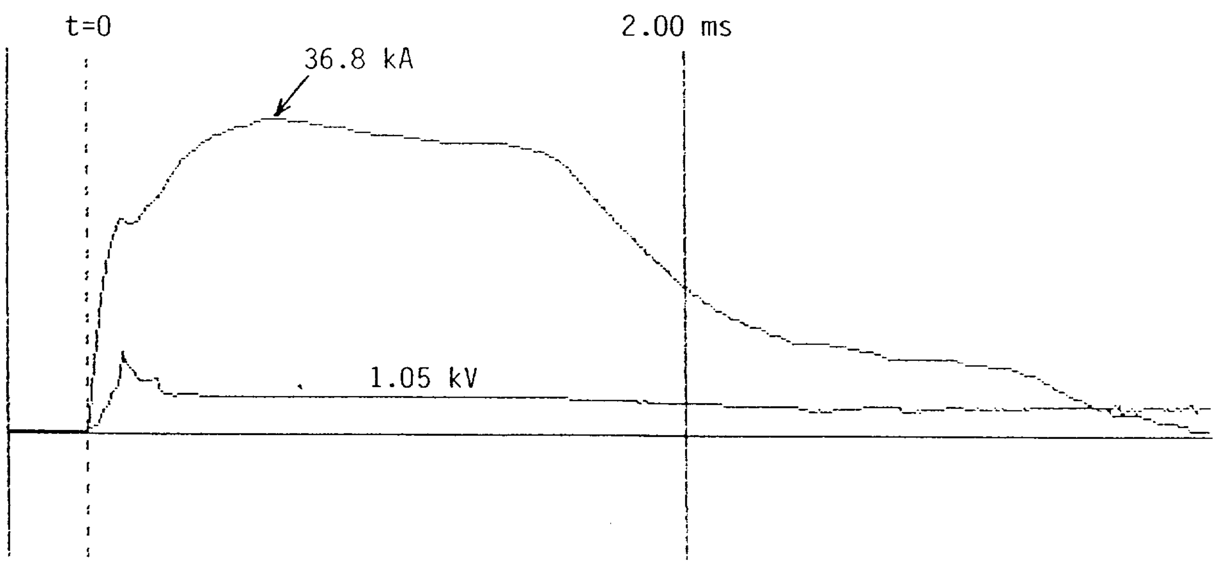


Figure 36. Current and voltage from Shot 23. Second successful wind tunnel shot without arc quenching.

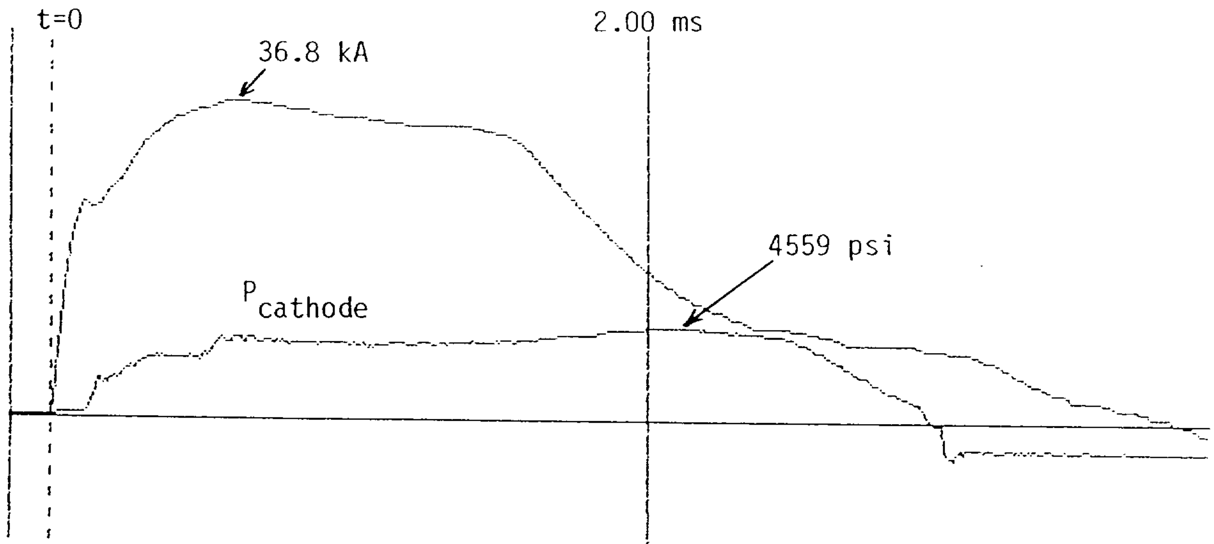


Figure 37. Pressure at capillary exit electrode from Shot 23. Current is shown for reference.

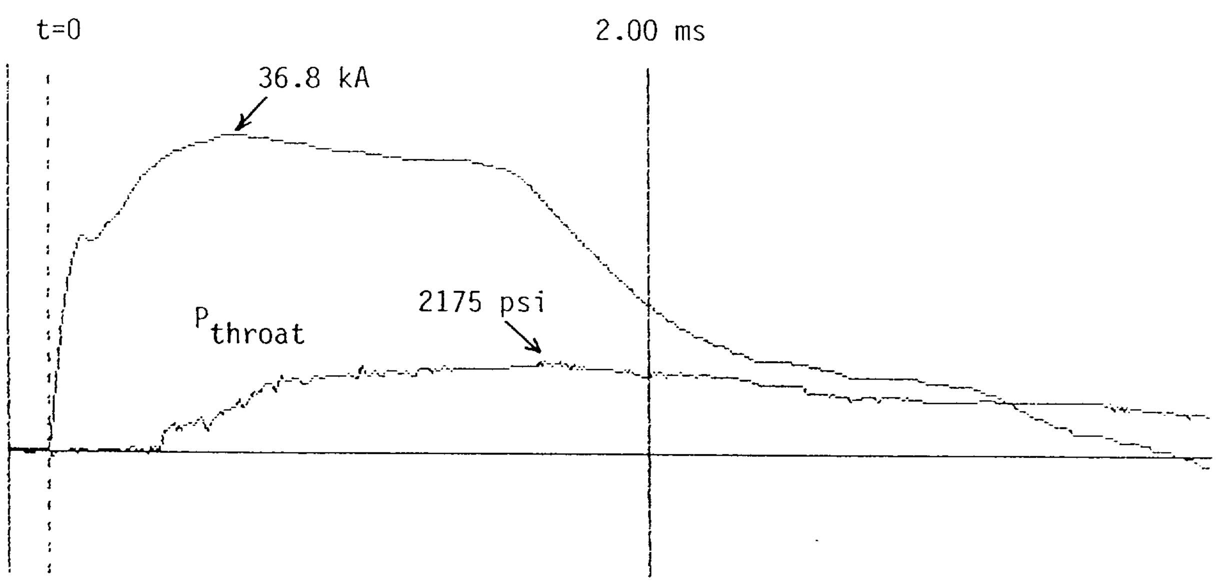


Figure 38. Pressure at nozzle throat from Shot 23. Current is shown for reference.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 1991	Contractor Report

4. TITLE AND SUBTITLE

Mach 10 to 20 Electrothermal Wind Tunnel Feasibility Study and Demonstration
Vol. II, Experimental Results

5. FUNDING NUMBERS

C NAS1-18450, Task 20

WU 505-62-40-02

6. AUTHOR(S)

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8. PERFORMING ORGANIZATION REPORT NUMBER

GASL TR-342

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

NASA Langley Research Center
Hampton, VA 23681-0001

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

NASA CR-191427, Volume II

11. SUPPLEMENTARY NOTES

Langley Technical Monitor: Allen G. McLain

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Unclassified - Unlimited

Subject Category 09

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The objective of the experimental effort was to demonstrate operation of the key component of the Electrothermal Wind Tunnel (EWT), the liquid capillary arc in a subscale, pulsed-type test bed. Operation of the liquid capillary arc requires pumping a cryogenic liquid into a tube of large length-to-diameter ratio maintaining a continuous arc discharge in the tube and producing a stable effluence of high-pressure, high-temperature vaporized gas suitable for expansion through a supersonic nozzle. The primary goal of this effort was production of up to 0.5 kg/sec of air at a pressure of 10,000 psi (ultimately 60,000 psi) and temperature of 20,000° K for a period of 2 milliseconds. These conditions were chosen to match the capacity of the available capacitor bank at GT-Devices.

14. SUBJECT TERMS

Electrothermal Wind Tunnel
Liquid Arc
Airbreathing Research Facility

15. NUMBER OF PAGES

61

16. PRICE CODE

A04

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	